National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science

Alaskan National Park Glaciers - Status and Trends

First Progress Report

Natural Resource Data Series NPS/AKR/NRDS—2012/403

ON THE COVER
Margerie Glacier in July 2011 with Grand Pacific Glacier debris-covered terminus in foreground. Glacier Bay National Park and Preserve July 13, 2011.
Photograph by: JT Thomas

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The National Park Service, Natural Resource Stewardship and Science office in Fort Collins, Colorado publishes a range of reports that address natural resource topics of interest and applicability to a broad audience in the National Park Service and others in natural resource management, including scientists, conservation and environmental constituencies, and the public.

The Natural Resource Data Series is intended for the timely release of basic data sets and data summaries. Care has been taken to assure accuracy of raw data values, but a thorough analysis and interpretation of the data has not been completed. Consequently, the initial analyses of data in this report are provisional and subject to change.

All manuscripts in the series receive the appropriate level of peer review to ensure that the information is scientifically credible, technically accurate, appropriately written for the intended audience, and designed and published in a professional manner.

This report received informal peer review by subject-matter experts who were not directly involved in the collection, analysis, or reporting of the data.

This report is available from the Natural Resource Publications Management website (http://www.nature.nps.gov/publications/nrpm/).

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NPS 953/117458, October 2012

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Executive Summary

This is the first progress for a multi-year study of glaciers in Alaskan national parks. The project will be completed in December 2013. Here we present results from mapping of all glacier extents in Glacier Bay National Park and Preserve (NP&P) and Denali NP&P, from measurements of surface elevation changes on select glaciers in Glacier Bay NP&P, and from focus glacier research on Brady, Margerie, and Muir Glaciers in Glacier Bay NP&P. We have accomplished all tasks on schedule for this first deliverable, and we look forward to continued conversation with our colleagues at NPS as the project moves forward. Significant early results include the following:

- Glacier Bay National Park and Preserve was 53.5% glaciated in 1952, but ice cover diminished 11% by 2010, to become 48.4% glaciated (6427 km^2).

- Denali National Park and Preserve was 16.9% glaciated in 1952, but ice cover diminished 8% by 2010, to become 15.5% glaciated (3817 km^2).

- The vast majority of glaciers in both parks have shrunk considerably, mainly by terminus retreat, in that time.

- A few glacier termini advanced in Glacier Bay since 1952. All these advances are by tidewater or recently-tidewater glaciers in retracted positions that may indicate a resumption of normal tidewater glacier expansion.

- Only two significant glacier expansions occurred in Denali since 1952. Both were surge-type glaciers: Muldrow and Peters Glaciers. Some smaller expansions were found.

- Using laser altimetry, we measured 32 distinct intervals of elevation change distributed among sixteen glaciers in Glacier Bay between 1995 and 2011. Of these measured intervals, all had negative glacier-wide mass balance rates (overall thinning) with five exceptions: positive rates on Muir Glacier 2005-2009 and 2009-2011 and Margerie Glacier 2005-2009, 2009-2011, and one neutral interval (Lamplugh Glacier 2009-2011).

- The lowest measured balance rate (greatest thinning) was on Grand Pacific Glacier from 2001-2009: ice loss average 1.99 m/yr over the entire glacier surface.

- We visited eleven of the 20 selected focus glaciers in summer 2011, including all three of the Glacier Bay focus glaciers: Brady, Margerie, and Muir. NPS personnel at many parks were extremely helpful in facilitating the visits and sharing information.

Acknowledgments

We acknowledge the advice and contributions of our NPS collaborators Bruce Giffen, Guy Adema, Fritz Klasner, and Rob Burrows. Additional analytical work was provided by Sam Herreid and Austin Johnson at UAF. Field support for focus glacier work at Glacier Bay was kindly provided by Lewis Sharman, Justin Smith, Tania Lewis, Bill Eichenlaub, and Rusty Yerxa. Finally, we thank all the many scientists whose work has helped build the foundation upon which this project is built.

Introduction

Project Overview

Basic information on the extent of glaciers and how they are responding to climatic changes in Alaska NPS units is lacking. Because glaciers are a central component of the visitor experience for many Alaskan parks, because the complicated relationship between glaciers, humans, and the climate system constitutes a significant interpretive challenge for NPS staff, and because glacier changes affect hydrology, wildlife, vegetation, and infrastructure, this project was initiated to document the status and recent trends in extent of glaciers throughout the nine glaciated park units in Alaska. The work will also be of substantial interest to scientists who recognize recent changes in Alaskan glaciers, including their collective contribution to sea level rise, as both globally significant and under-studied.

Of Alaska’s 15 national parks, preserves, and monuments, nine contain or adjoin glaciers: Aniakchak (ANIA), Denali (DENA), Gates of the Arctic (GAAR), Glacier Bay (GLBA), Katmai (KATM), Kenai Fjords (KEFJ), Klondike Gold Rush (KLGO), Lake Clark (LACL), and Wrangell-St. Elias (WRST). Under this project, status and trends of glaciers within (or in isolated cases—adjacent to) these park units will be assessed in three primary ways: changes in extent (area) for all glaciers, changes in glacier volume for all glaciers with available laser altimetry, and an interpretive-style description of glacier and landscape change for 1-3 “focus glaciers” per park unit. These components of the project, summarized in Table 1, are described in more detail in the methods section of this report.

Table 1. Overall scope of project by component: PI, glacier coverage, and types of analyses.

	Extent Mapping	Volume Change	Focus Glaciers
Principal Investigator	Dr. Anthony Arendt	Dr. Chris Larsen	Dr. Michael Loso
Affiliation	Geophysical Institute, University of Alaska Fairbanks	Geophysical Institute, University of Alaska Fairbanks	Environmental Science Dept, Alaska Pacific University
Contact	arendta@gi.uaf.edu	chris.larsen@gi.uaf.edu	mloso@alaskapacific.edu
Analyses	Map modern and historic outlines of glaciers from topo maps and satellite imagery	Determine glacier surface elevation changes over time with repeat laser altimetry	Graphic/narrative summary of glacier response to climate and landscape-scale impacts
Glacier Coverage	All glaciers in all units, some park-adjacent glaciers	Existing coverage: ~1000 total flightlines in parks	1-3 per park unit

Project Deliverables and Timeline

The results of our work will be presented in two written products: a technical report and an interpretive report. Dr. Loso has primary responsibility for the content of both publications – NPS will provide layout and production.

The technical report, published internally as a Natural Resource Technical Report, will be a comprehensive technical document prepared to thoroughly document the data sources, methodology, and results of the project, to analyze those results, and to discuss the implications of those analyses. The technical report will be accompanied by a permanent electronic archive of geographic and statistical data and is intended to serve a specialized audience interested in working directly with the project's datasets. It will therefore be complete, lengthy, and cumbersome to read for scientists interested primarily in the project's findings and implications. Those audiences will find a comprehensive, but more accessible, discussion of the project's results and implications in the interpretive report, discussed below.

The interpretive report will be a non-technical document suitable for glaciologists, park interpretation specialists, park managers, and park visitors with no particular background in science or glaciology. The document will be comprehensive and thorough, however, and is envisioned as graphics and photo-intensive, content rich, and accessibly written. Content will be prepared to fit in a publication similar to an existing model: [Winkler GR. 2000. A Geologic Guide to Wrangell-St. Elias National Park and Preserve, Alaska. USGS Professional Paper 1616, 166 pp.] Content will include a comprehensive literature review, and also detailed—but accessible—summaries of the key data sources, methodologies, and findings of the technical report. We will utilize the "focus glaciers" as a primary narrative tool to describe status and trends in NPS glaciers.

Separately from these primary publications, the principal investigators—in collaboration with other research associates and NPS staff, as appropriate and willing—will publish the research results of most broad and compelling scientific interest in a more concise form in one or more peer-reviewed journals (e.g. Journal of Glaciology). These articles are not considered project deliverables. Interpretive summaries may also be produced based on region-wide and/or park-by-park themes. These 2 page (front and back) summaries, published internally by NPS, would summarize the most broad and compelling findings of scientific interest.

The project was initiated with a kickoff meeting held October 11, 2010 and is scheduled for completion December 15, 2013. Interim project tasks and deliverables are summarized in Table 2, and are subject to modification in each year's annual meeting and task agreement.

Scope of Progress Report 1

This is the first of four progress reports due biannually during the first two years of the project (Table 2). These reports, as described in minutes of the October 2010 kickoff meeting, are meant to be technical in nature and park-centered. They may contain some analysis on parks with completed data products, and in other cases may simply present data products that remain incomplete. Parks scheduled for presentation in this report are Glacier Bay (all project components) and Denali (extent mapping only).

The principal investigators recognize the uniqueness of this report as our first substantive written communication to the project sponsors. In light of that, we welcome close examination of the document as a whole. Sections like the introduction and methods may appropriately be skimmed in subsequent progress reports, but at this stage we actively encourage feedback from all readers on the scope of the project, our approach, and the projected deliverables. Much of our work on this project over the last year has been devoted to those items, and it will be helpful—as our focus turns towards generating and analyzing data—to know that we are moving in the right direction.

Table 2. Schedule for project tasks and deliverables. Report is under the direction of Loso, but relies substantially on timely contribution by all collaborators.

Date	Extent Mapping-Arendt	Volume Change-Larsen	Focus Glaciers-Loso	Reporting-Loso et al.
9/30/11	Glacier Bay, Denali	Glacier Bay	Glacier Bay	Progress Report 1
3/30/12	Katmai, Lake Clark	Katmai, Lake Clark	Summary of field efforts*	Progress Report 2
9/30/12	Gates of the Arctic, Klondike, Aniakchak	Denali	Katmai, Lake Clark, Denali	Progress Report 3
3/30/13	Kenai Fjords, Wrangell-St. Elias	Kenai Fjords, Wrangell-St. Elias	Summary of field efforts*	Progress Report 4
5/31/13	Remaining data and analyses	Remaining data and analyses	Remaining data and analyses	Progress Report 5
9/30/13			Report prep	Draft Final Report
11/1/13	Report review	Report review		
12/15/13			Report prep	Final Report

* only as dictated by actual fieldwork

Study Areas

Alaska is the largest and most heavily glaciated of the fifty United States. With an area of 1,530,693 km^2, approximately 75,000 km^2, or ~5% of the land area, are covered by glacial ice (Post and Meier, 1980). The number of glaciers in the state is not precisely known, but probably exceeds 100,000 (Molnia, 2001). Approximately 18,500 km^2 of the state's glaciers (~25%) are on lands administered by the National Park Service. Statewide, NPS administers 15 national parks, preserves, monuments, and national historical parks; glaciers occur in (or adjacent to, in the case of Klondike Gold Rush) 9 of those units:

- Aniakchak National Monument and Preserve
- Denali National Park & Preserve
- Gates of the Arctic National Park & Preserve
- Glacier Bay National Park & Preserve
- Katmai National Park & Preserve
- Kenai Fjords National Park
- Klondike Gold Rush National Historic Park
- Lake Clark National Park & Preserve
- Wrangell-St. Elias National Park & Preserve

This progress report focuses on two of those units: Glacier Bay and Denali (Figure 1). We describe these in more detail below. Subsequent progress reports, and the final report, will address glacier status and trends in the other 7 units.

Denali's glaciers (including glaciers wholly or partly inside of the Park boundary) covered around 3820 km^2 as of August 2010. Most flow either NW or SE off the central spine of the SW-trending Alaska Range. The longest and largest glaciers in the park are on the south side of the range; the largest is Kahiltna Glacier—over 70 km long. The glaciers range from 62˚ 17' N to 63˚ 28' N and from 149˚ 01' W to 152˚ 53' W. The glaciers are contiguous with additional ice-covered terrain further east and west along the continuation of the Alaska Range outside the Park boundaries. Many glaciers in Denali, especially north of the Range, exhibit surge-type behavior.

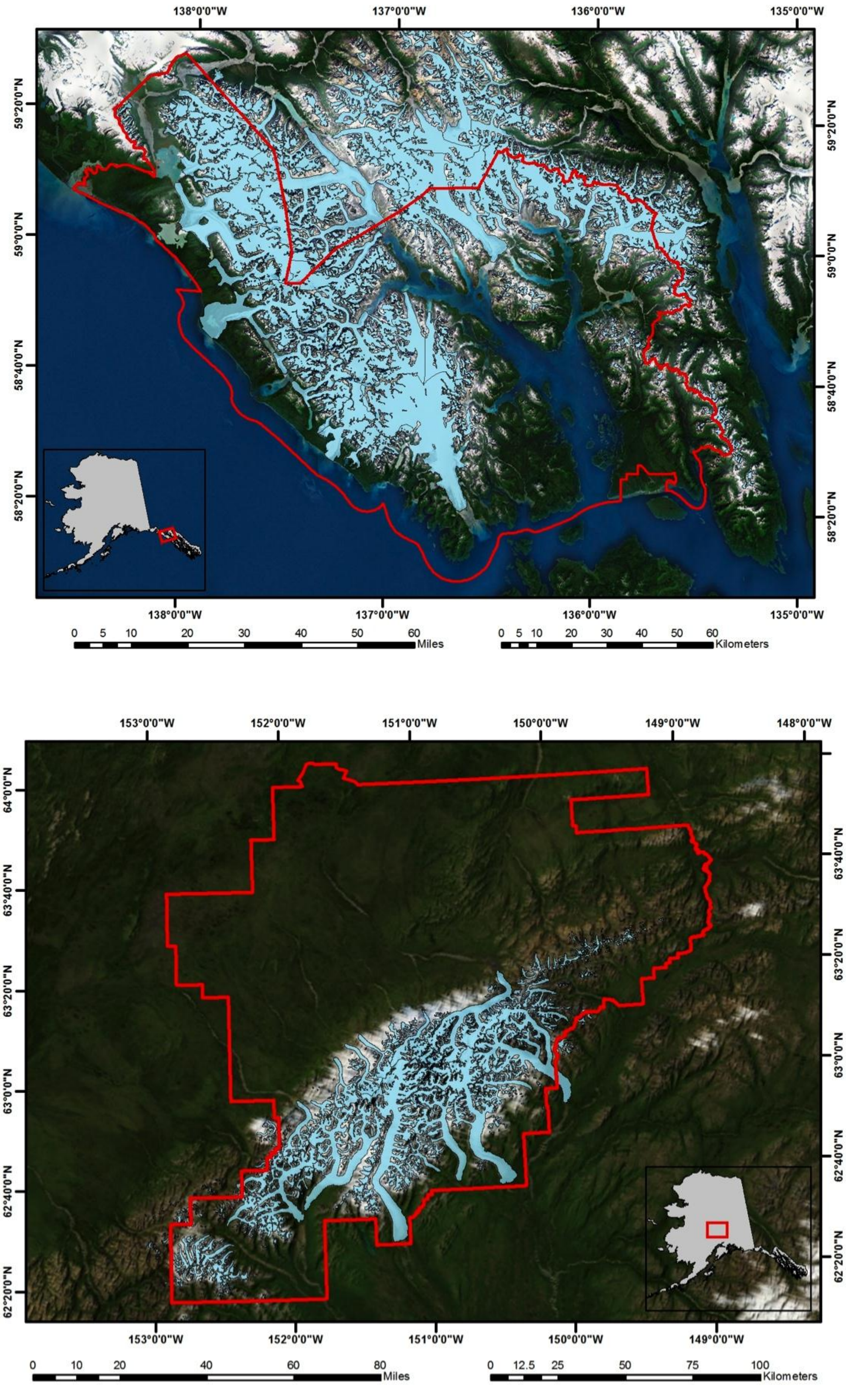


Figure 1. Study areas for this progress report: Glacier Bay National Park and Preserve (upper panel) and Denali National Park and Preserve (lower panel). Blue polygons are current ice coverage, red lines are park outlines.

Glacier Bay National Park and Preserve

Glacier Bay National Park and Preserve is located directly adjacent to the Gulf of Alaska, west of Haines and northwest of Juneau. The Park was first established in 1925 (as a National Monument) and expanded to its present size and designation in 1980. It contains 13,287 km^2 of federal land. The vast mountains of the Fairweather Range, the Alsek Range, and the Chilkat Range are the result of the collision of the North American and Pacific tectonic plates at the Queen Charlotte-Fairweather fault. Mount Fairweather, which is only 25 km from the Pacific Ocean, is the highpoint of the Fairweather Range at 4,671 m and is the source of the Margerie, Grand Plateau, and Fairweather Glaciers. The maritime climate created by the Pacific Ocean, combined with the large vertical relief of the mountains, results in copious amounts of precipitation that feed the accumulation areas of the region. Near park headquarters, average January low temperature is -5° C and average July high is 18° C. Annual precipitation is 177 cm.

Glacier Bay NP&P (including glaciers wholly or partly inside of the Park boundary) has an ice-covered area of around 6430 km^2 as of August 2010. The Icefield is arrowhead shaped and ranges from 58˚ 19’ N to 59˚ 24’ N and spans from 135˚ 28’ W to 138˚ 11’ W. There are two distinct areas of ice coverage: the glaciers located in the Fairweather Range, which includes Grand Pacific and Brady Glaciers, and those located northeast of the West Arm of Glacier Bay in the Alsek and Chilkat Ranges, which includes Carroll and Muir Glaciers. These two areas were previously part of the much more extensive Glacier Bay Icefield that has experienced a massive glacial retreat since the end of the Little Ice Age (LIA). This retreat has been substantially influenced by the fact that many of Glacier Bay’s glaciers terminated in tidewater and still do.

Denali National Park and Preserve

Denali National Park & Preserve is located in interior Alaska, north of Anchorage and south of Fairbanks. The Park was first established in 1917 (as Mt. McKinley National Park) and expanded to its present size and designation in 1980. It contains 24,585 km^2 of federal land. In Denali NP&P, the Alaska Range attains its greatest height, containing the highest mountain in North America (Denali or Mt. McKinley, 6194 m) and numerous summits over 3000 m. The interior climate of Denali is cold in winter and warm in summer, with dry conditions and modest snowfall at low elevations but higher levels of precipitation in the mountains, especially on the south side of the range. Near park headquarters, average January low temperature is -22° C and average July high is 21 C. Annual precipitation is 37 cm.

Methods-Mapping

Data

The mapping component of this project aims to delineate the outlines of all glaciers in all Alaskan parks for two time intervals: mid-20th century (based mainly upon USGS topographic mapping from that time period) and the early 2000s (based upon latest available satellite imagery). Detailed source information for mapping presented in this report is presented in Table 3. At present, we are doing all mapping on multispectral Landsat data with acquisition years ranging from 2003-2010, although using SPOT imagery in some cases where features were difficult to resolve using Landsat alone. Topographic map coverage is based on photography that dates back as early as 1948 and as late as 2008. The recent data are anomalous in a dataset dominated by 1950s photos: the mean photographic year was 1956 and the median year was 1952 (Table 3). For simplicity, we subsequently refer to these time intervals as "map date" (nominally 1952) and "modern" (2010)

Analysis

PI Anthony Arendt and research technician Justin Rich have developed a standardized workflow for the generation and distribution of glacier shapefiles and associated geostatistics for these glaciers (Figure 2). We have automated the procedure whenever possible to minimize errors, and to provide for future outline generation after this project is complete. Justin Rich has developed algorithms that provide for automatic delineation of glacier boundaries from multispectral satellite imagery, and has also produced an algorithm to improve the usability of post-2003 Landsat imagery that is corrupted by scan line correction (SLC) errors.

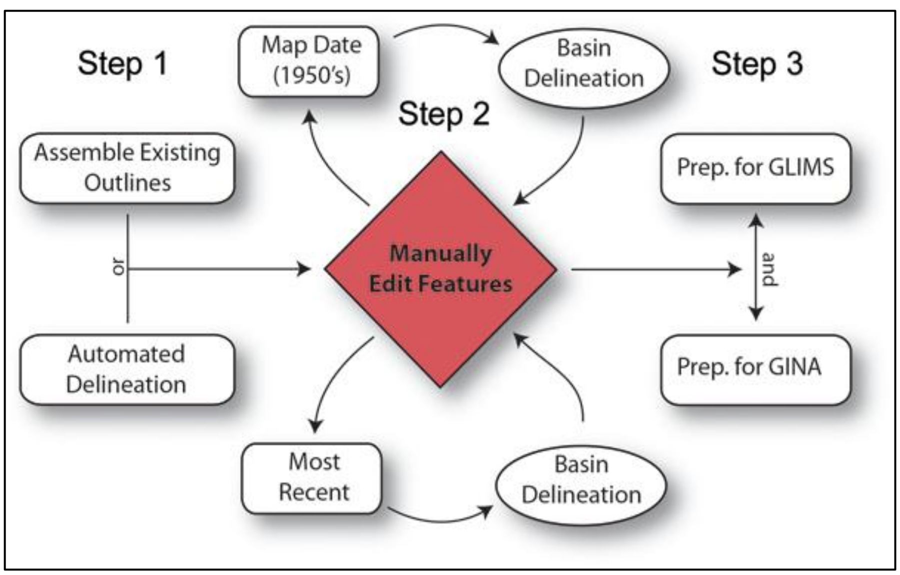


Figure 2. Workflow for the generation of glacier inventory data for NPS glaciers.

Table 3. Data sources for mapping. Above: sources for modern satellite imagery. Below: historic maps. All are USGS 1:63000 quads in NAD1927:units feet, except “Gov’t of Canada”:NAD1983 units meters.

Park	FileID	Date	Long (center)	Lat (center)	Type
GLBA	LE70590192010259EDC00	9/16/10	-136.539268442000	58.712357493200	LANDSAT7 ETM+
GLBA	LE70600192010266EDC01	9/23/10	-138.108487640000	58.709849039100	LANDSAT7 ETM+
DENA	LE70700162003221EDC01	8/9/03	-150.614579265334	62.856765477687	LANDSAT7 ETM+
DENA	LE70710162004231EDC02	8/18/04	-152.166639577574	62.858856256340	LANDSAT7 ETM+
DENA	LE70700162009189EDC01	7/8/09	-150.619110606315	62.851987852667	LANDSAT7 ETM+
DENA	LE70710162007223EDC00	8/11/07	-152.169519019058	62.854432081344	LANDSAT7 ETM+
DENA	LT50710162010255GLC00	9/12/10	-152.185439381545	62.842390026986	LANDSAT5

Park	FileID	Pub Year	Photo Year	Revisions
GLBA	SKAGWAY A-5	1961	1951	
GLBA	MT FAIRWEATHER C-4	1961	1955	
GLBA	JUNEAU D-6	1949	1948	Limited Revisions 1972
GLBA	JUNEAU B-4	1949	1948	Minor Revisions 1972
GLBA	MT FAIRWEATHER C-5	1961	1951	
GLBA	JUNEAU C-4	1949	1948	Minor Revisions 1978
GLBA	MT FAIRWEATHER D-4	1961	1955	
GLBA	MT FAIRWEATHER C-3	1961	1955	
GLBA	YAKUTAT A-1	1959	1953	
GLBA	MT FAIRWEATHER B-2	1948	1948	Minor Revisions 1971
GLBA	MT FAIRWEATHER C-2	1948	1948	Minor Revisions 1973
GLBA	JUNEAU C-5	1948	1948	Minor Revision 1973
GLBA	SKAGWAY B-8	1961	1951	
GLBA	SKAGWAY A-8	1961	1951	
GLBA	MT FAIRWEATHER D-6	1961	1955	
GLBA	SKAGWAY B-4	1954	1948	Minor Revisions 1972
GLBA	MT FAIRWEATHER D-1	1985	1948	
GLBA	SKAGWAY A-7	1961	1951	
GLBA	SKAGWAY A-2	1954	1948	Limited Revisions 1977
GLBA	SKAGWAY A-3	1954	1948	Limited Revisions 1972
GLBA	MT FAIRWEATHER D-2	1948	1948	Minor Revision 1991
GLBA	MT FAIRWEATHER B-4	1961	1951	
GLBA	JUNEAU D-5	1949	1957	Minor Revision 1995
GLBA	JUNEAU B-5	1950	1948	Minor Revision 1966
GLBA	SKAGWAY A-6	1961	1951	
GLBA	JUNEAU C-6	1950	1948	Minor Revision 1987
GLBA	MT FAIRWEATHER B-3	1961	1955	
GLBA	MT FAIRWEATHER D-3	1961	1955	
GLBA	SKAGWAY A-4	1961	1955	Limited Revisions 1972
GLBA	SKAGWAY B-3	1954	1948	Minor Revisions 1963
GLBA	YAKUTAT B-1	1959	1953	
GLBA	MT FAIRWEATHER D-5	1961	1955	
GLBA	MOUNT ROOT v3.0	2010	1979	Gov't of Canada 1:50000
GLBA	MOUNT LODGE v3.0	2010	1987	Gov't of Canada 1:50000
GLBA	GRAND PACIFIC GLACIER v3.0	2010	1987	Gov't of Canada 1:50000
GLBA	KONAMOXT GLACIER v3.0	2010	1987	Gov't of Canada 1:50000
GLBA	CARMINE MOUNTAIN v3.0	2010	1987	Gov't of Canada 1:50000
GLBA	CARMINE MOUNTAIN v4.0	2010	2008	Gov't of Canada 1:50000
GLBA	PENTICE RIDGE v3.0	2010	1987	Gov't of Canada 1:50000
GLBA	TSIRKU GLACIER v3.0	2010	1987	Gov't of Canada 1:50000
GLBA	CARROLL GLACIER v3.0	2010	1987	Gov't of Canada 1:50000
GLBA	YAKUTAT B-2	1959	1948	Minor Revisions 1991
GLBA	MT FAIRWEATHER D-7	1961	1948	
DENA	HEALY A-6	1981	1949	Minor Revisions 1987
DENA	MT MCKINLEY B-1	1954	1952	Minor Revisions 1995
DENA	TALKEETNA B-6	1958	1957	Minor Revision 1986
DENA	TALKEETNA C-4	1973	1953	Minor Revisions 1973
DENA	TALKEETNA D-1	1958	1953	Minor Revisions 1971
DENA	MCGRATH C-1	1958	1957	Minor Revisions 1982
DENA	HEALY B-6	1954	1953	Minor Revisions 1981
DENA	TALKEETNA D-4	1976	1952	Limited Revisions 1976
DENA	MT MCKINLEY B-2	1954	1952	Minor Revisions 1994
DENA	TALKEETNA C-5	1976	1955	Limited Revisions 1976
DENA	TALKEETNA C-1	1958	1952	Minor Revisions 1974
DENA	TALKEETNA A-6	1958	1957	Minor Revisions 1973
DENA	MCGRATH B-1	1958	1955	
DENA	TALKEETNA D-2	1958	1952	
DENA	MT MCKINLEY A-1	1954	1954	Minor Revisions 1991
DENA	HEALY B-5	1983	1951	Minor Revisions 1983
DENA	TALKEETNA D-5	1958	1952	Minor Revisions 1978
DENA	TALKEETNA D-3	1958	1952	Minor Revision 1973
DENA	MT MCKINLEY A-4	1953	1952	Minor Revisions 1967
DENA	TALKEETNA C-2	1977	1954	Limited Revisions 1977
DENA	TALKEETNA C-6	1958	1957	Limited Revisions 1977
DENA	TALKEETNA C-3	1958	1953	
DENA	TALKEETNA B-3	1958	1953	Minor Revisions 1980
DENA	HEALY C-5	1973	1951	Minor Revisions 1973
DENA	MT MCKINLEY A-3	1954	1952	
DENA	TALKEETNA MTNS D-6	1951	1949	Minor Revisions 1966
DENA	TALKEETNA A-5	1975	1957	Limited Revisions 1975
DENA	MT MCKINLEY A-2	1954	1952	Minor Revisions 1978
DENA	TALKEETNA B-5	1995	1955	Minor Revisions 1995

Details of the workflow shown in figure 1 are described below, and the steps are shown by example in Figure 3.

Step 1: Existing outlines are assembled if they exist. These may come from previous UAF altimetry work or from colleagues working on these areas. Otherwise, an automated delineation algorithm is run using multispectral satellite imagery to produce a first estimate of glacier extent.

Step 2: We perform heads-up (on-screen) manual digitization on the computer to clean up existing outlines so that they more accurately match map or satellite imagery. Editing is performed at approximately 1:2,000 scale. Once the product is of suitable quality, we run it through a basin delineation algorithm written by UAF PhD student Christina Keinholz. This requires identification of a series of pour-points that the algorithm uses to isolate specific glacier basins. We perform additional manual digitization, primarily to ensure the automatically-produced basins match what we would expect in reality. We then populate the attribute table with glacier names (where available), calculate glacier areas, and use a GLIMS-standard code to describe glacier types: e.g. surge-type, tidewater, etc. (Rau et al. 2005).

Step 3: We run a final series of scripts that set up the files for ingest into each of two data distribution formats. As part of this step we write metadata files that describe what imagery was used, what dates are covered, and other information summarized by Table 3. Data are then uploaded to the Global Land Ice Measurements from Space (GLIMS) data portal and we work with technicians at NSIDC to solve any remaining issues. We are also preparing data for distribution to the Geographic Information Network of Alaska, an in-house data distribution portal that will give us more flexibility in the types of products we produce. Two products are exported from these final scripts: a geostatistics file and a hypsometry file. The geostatistics file lists, for each glacier:

- Glacier ID
- Name (if available)
- Date of imagery used
- Centroid latitude and longitude
- Glacier area
- Min, max, Kurowsky, and area-weighted mean glacier elevation
- Slope (mean, SD)
- Aspect (mean, SD)

Detailed field definitions are provided in Appendix C. The hypsometry file has a row for each glacier and multiple columns representing elevation bands (in 50 m bins) on the glacier. The cell entry in these rows is the area of the glacier within that elevation range. NRDS reports are less formal than other nationally published reports, and are inherently more flexible with respect to style and format. They are intended for the sharing basic data sets within the NPS and with associated project and research partners, and require little or no data analysis.

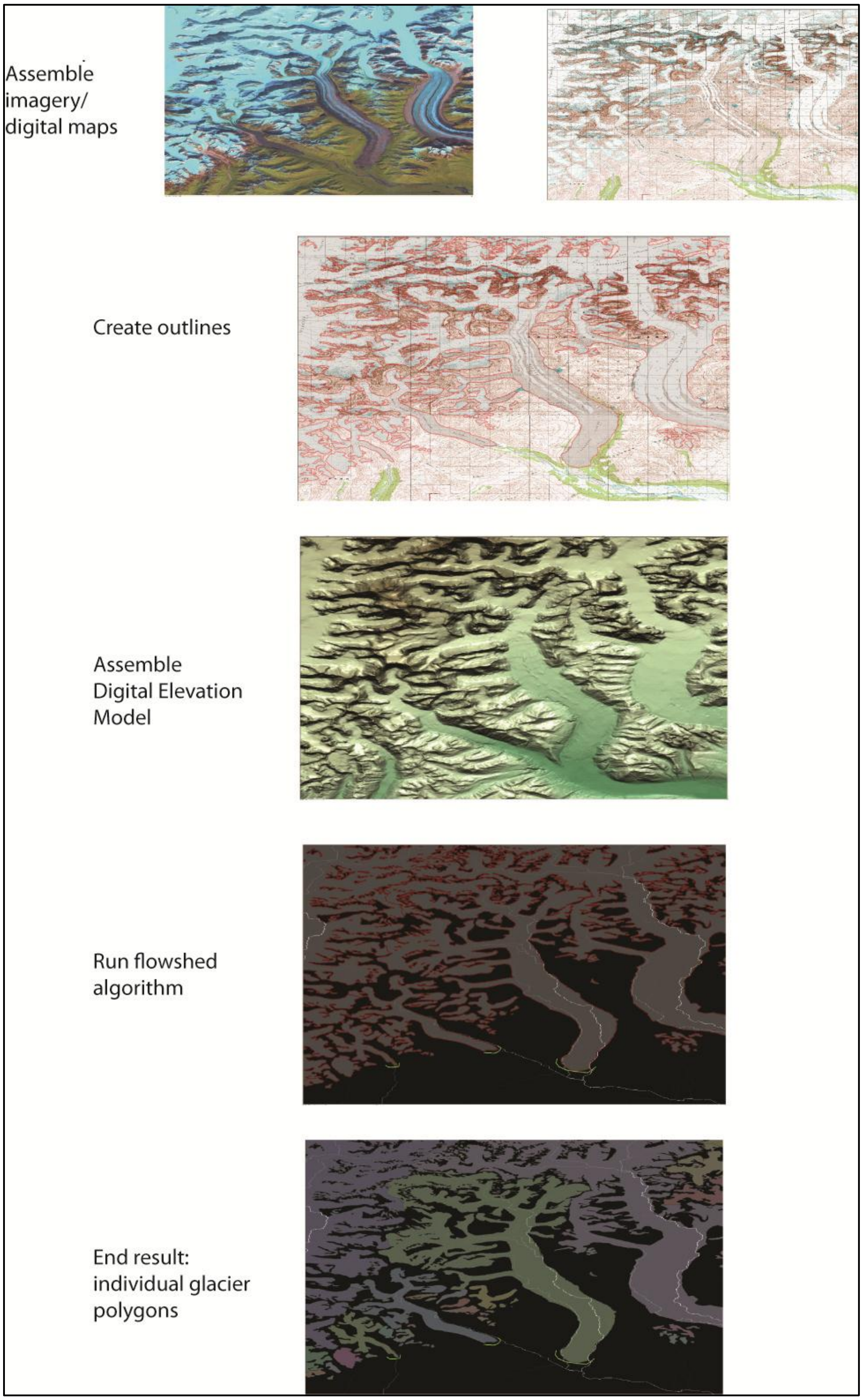


Figure 1. Imagery (from Tokositna and Ruth Glaciers, Denali NP&P) demonstrating generation of glacier inventory data for NPS glaciers

Methods-Elevation Change

The elevation change component of this project aims to characterize changes in surface elevations of all glaciers (within glaciated Alaskan parks) that have existing laser point data from one or more time intervals since this work commenced in the mid 1990s. No new laser altimetry data will be acquired under the scope of this project. Existing laser altimetry profiles (as of January 2011) for Glacier Bay are shown in Figure 4 and Table 4. The glaciers selected for laser altimetry include a wide variety of glacier types (tidewater, lake calving, land terminating, and surge type) and most of the major glaciers of the Glacier Bay Icefield are included. Glaciers with areas over 100 km^2 that are not included are Johns Hopkins (253 km^2), LaPerouse (124 km^2), and McBride Glaciers (119 km^2).

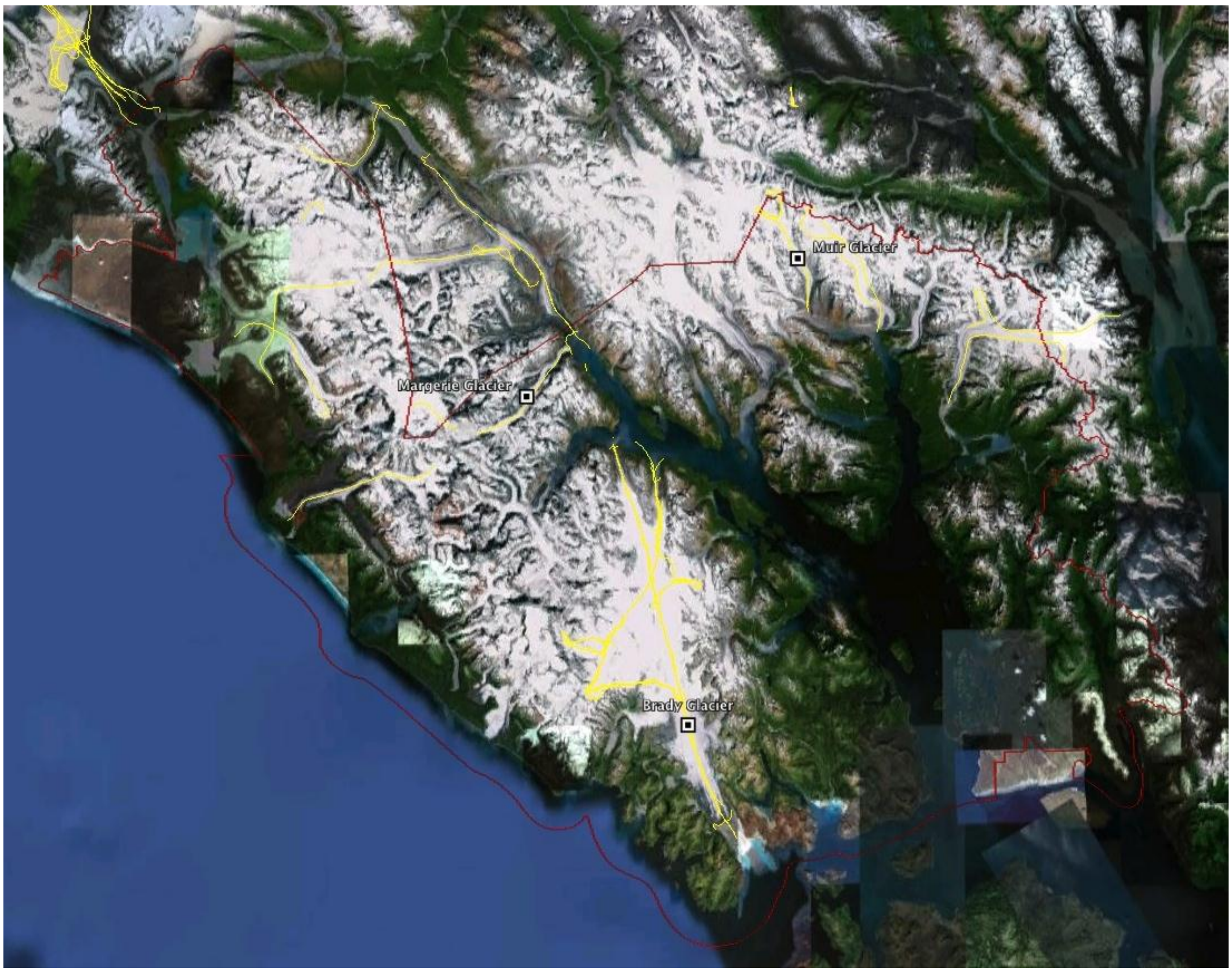


Figure 2. Existing laser altimetry profiles (yellow lines) in Glacier Bay National Park and Preserve (red polygon) as of January 2011. Focus glacier locations are also shown. Base map courtesy Google Earth.

Data

Elevation change estimates are based upon laser point data acquired from aircraft at discrete time intervals. Laser point data has been acquired with three different systems since data collection began in 1995, including two different laser profilers before 2009 and a scanning laser system since then. The laser profilers have been described in previous publications (Arendt et al. 2002; Echelmeyer et al. 1996; Sapiano et al. 1998). The data acquired during those earlier missions have been reprocessed with the same methods as post-2009 data, which was acquired with a Riegl LMS-Q240i that has a sampling rate of 10,000 points per second, an angular range of 60 degrees, and a wavelength of 900 nm. The average spacing of laser returns both along and perpendicular to the flight path at an optimal height above glacier of 500 m is approximately 1 m x 1 m with a swath width of 500 – 600 m. The aircraft is oriented using an inertial navigation system (INS) and global position system (GPS) unit. The INS is an Oxford Technical Solutions Inertial+ unit that has a positioning accuracy of 2 cm, a velocity accuracy of 0.05 km/h RMS, and an update rate of 100 Hz. The GPS receiver is a Trimble R7 that records data at 5 Hz and has an accuracy of 1 cm horizontal and 2 cm vertical in ideal kinematic surveying conditions.

To translate laser point data to estimates of volume change, we require digital elevation models (DEMs) and glacier outlines for measured glaciers. The DEM is derived from Shuttle Radar Topography Mission (SRTM) data acquired in February of 2000 (Rabus et al. 2003). Outlines and surface areas of each glacier are based upon Landsat 7 images from August 1999 and August 2010, and on USGS topographic maps from the 1950s.

Table 4. Date of laser altimetry flights for glaciers located in Glacier Bay National Park and Preserve. All profiles were acquired during the last week of May and the first week of June. Glacier types are land terminating (L), lake calving (LK), tidewater (T), and surge (S).

Brady (L)	Lamplugh (T)	Reid (T)	Grand Pacific (T)	Muir (L)	Margerie (T/S)	Riggs (L)	Casement (L)
6/4/95	6/4/95	6/4/95	6/6/96	5/27/00	6/2/05	6/1/05	6/1/05
5/24/00	5/24/00	5/24/00	6/6/01	6/1/05	6/2/09	6/2/09	6/2/09
6/1/05	6/1/05	6/1/05	6/2/09	6/2/09	5/30/11	5/30/11	5/30/11
6/2/09	6/2/09	6/2/09	5/30/11	5/30/11			
5/30/11	5/30/11	5/30/11					
Davidson (LK)	**Grand Plateau (LK)**	**Fairweather (L)**	**Carroll (L/S)**	**Tkope (L)**	**Little Jarvis (L)**	**Melbern (LK)**	**Konamoxt (L)**
6/1/05	6/2/05	6/2/05	6/2/09	6/2/09	5/31/95	6/6/96	6/696
6/2/09	6/2/09	6/2/09	5/30/11	5/30/11	5/28/00	6/6/01	5/30/11
5/30/11	5/30/11						

Analysis

The workflow for calculation of elevation changes and derived volume changes follows these steps:

Step 1: Glacier surface elevations are derived from laser point data by integrating the GPS-based position of the aircraft on its flight path over a glacier, airplane orientation data from an onboard INS, and laser point return positions relative to the airplane. The combination of these data determines the position in 3-dimensional space of the laser point returns from the glacier surface. The points are referenced in ITRF00 and coordinates are projected to WGS84, with a coordinate accuracy in x, y, and z position of +/- 30 cm. Elevation data are recorded as height above ellipsoid.

Step 2: Glacier surface elevation profiles from different years can then be differenced to find the cumulative thickness change (dz, meters) over that time interval. Division by the time elapsed (dt, years) gives the rate of thickness change Δz (m/yr). This is determined with slightly different methods depending on whether data from the laser profiler (1995 – 2009) or laser scanner (2010 – 2011) are being used.

Step 3a: For laser profiler to laser profiler differencing, points that are located within 10 m of each other in the x-y plane are selected as common points between the different years. If more than one point is located within that 10 m grid, then the mode of the elevation is used for each grid point. These common points are then used in the determination of Δz. Since there are data points recorded only along the flight track at nadir with the laser profiler it is critical that these earlier flight paths were repeated as accurately as possible to obtain a large number of common points. Sometimes the flights were not repeated closely enough to provide extensive elevation change. This limits the robustness of the interpolated line that is fit to the data, especially if there is variability within the data.

Step 3b: For laser scanner to laser profiler differencing, a grid is made of the laser scanner swath at a resolution of 10 m. This grid is based upon the mode of all the points within each of the grid cells, which helps to filter out laser returns from crevasse bottoms. Then, the coordinates from each point in the old profile are used to extract an elevation from this grid (for all laser profiler points that fall within the new LiDAR swath extents). This laser scanner elevation is differenced with the laser profiler elevation at that point, giving the change in elevation. The same idea is used for laser scanner to laser scanner comparisons, but instead of using every point from the older laser scanner swath, an average value on a 10 m x 10 m is calculated out of the old swath, then the value for that point location is also extracted from the newer laser scanner grid.

Step 4: The complete series of Δz measurements at specific elevations along the glacier flight line is fit with an interpolated line by using a piecewise cubic polynomial, which is divided into bins covering 30 m of elevation. Δz is also tied to zero at both the lower and upper elevation limits of the glacier.

Step 5: The SRTM-based DEM is used to develop an area-altitude distribution for the glacier in 30 m bins that correspond to those used for the interpolation in step 4. Volume change is found by performing a numerical integration wherein the binned interpolated line is multiplied by the binned SRTM AAD.

To facilitate comparison of volume changes among glaciers of different sizes, we convert volume changes to glacier-wide mass balance rates ($\dot{B}$), adhering to terminology in the Glossary of Mass Balance Terms (Cogley et al. 2011). The volume change is calculated assuming that the lost (or gained) volume was composed entirely of ice, e.g. Sorge's law (Bader, 1954). Because the "before" data was acquired in mid-accumulation season (February) and the "after" data at the end of the accumulation season with a deeper snowpack (May/June), our data violate Sorge's law, in detail, and slightly underestimate annual thinning. We will quantify the expected magnitude of these concerns in the final report. In any case, volume change can then be converted to water equivalent (w.e.) by assuming a constant ice density of 900 kg/m3, and volume change presented as km^3/yr. Glacier-wide mass balance rate is then just volume change divided by glacier surface area.

Methods-Focus Glaciers

The focus glacier component of this project aims to provide additional information about a small subset of glaciers in each glaciated Alaskan park for the purpose of demonstrating the potentially unique ways in which A) glaciers change in response to climate and other forcings, and B) landscapes respond to glacier change. The focus glacier portion of the final report will include a narrative description of each glacier and a collection of photos, maps, figures, and other graphical information. In comparison with the other components of this project, which are directed clearly towards generating and analyzing new or existing data, the focus glacier component is focused more on interpretation and synthesis. No new data will be acquired, but collection of existing materials is a central task for the PI Michael Loso. For each glacier, this collection of materials will ultimately be presented as a "vignette" in the final document.

Focus Glacier Selection

The current and potentially final list of focus glaciers is included below (Table 5) and mapped in Figure 5. The list was originally compiled in October 2010 by the project's ad hoc working group [Bruce Giffen (NPS), Fritz Klasner (NPS), Guy Adema (NPS), Rob Burrows (NPS), Chris Larsen (UAF), Anthony Arendt (UAF), and Michael Loso (APU)]. The focus glaciers were not intended to be statistically representative of Alaskan glaciers as a whole, but rather were selected to collectively represent the diversity of glacier types and climatic responses evident statewide. Additional supporting criteria for inclusion in the list were a rich history of visitation/ documentation and public accessibility.

Since October 2010, the list evolved some under the advice and guidance of NPS staff, particularly including NPS unit resource staff and regional I&M staff. Key personnel involved in these discussions, aside from the project's working group, have thus far included (in no particular order) Chuck Lindsay, Craig Smith, Brendan Moynahan, Deb Kurtz, Lewis Sharman, Greg Streveler, Tom Liebscher, Jeff Rasic, Troy Hamon, Dave Schirokauer, Jim Lawler, and Page Spencer. This list includes only those who have actively participated in the discussion—feedback was solicited but not received from some other resource personnel.

Table 5. Focus glaciers for each of Alaska's 9 glaciated park units. "Snapshot" briefly denotes unique aspects of each glacier. PI Loso has personal knowledge of "visited" glaciers. Glaciers with a "poor" historic record may require additional work, outside the original scope, if they are to be included in the final report.

Park	Glacier(s)	Snapshot	Visited	Historic record
ANIA	Caldera icefields	Only permanent ice in Aniakchak. Virtually unstudied. Tiny.	no	poor
DENA	Kahiltna Glacier	Popular climbing and flightsee route. Non-surging valley glacier.	yes	good
	Muldrow Glacier	Backcountry accessible surge-type valley glacier.	yes	good
	Toklat Glacier	Backcountry accessible cirque glacier with history of NPS study.	no	good
GAAR	Arrigetch glaciers	High visitation for a remote park. Small, arctic cirque glaciers.	yes	good
GLBA	Brady Glacier	Remote tidewater glacier with very low-elev accumulation zone.	yes	good
	Margerie Glacier	Cruise-ship visible, tidewater. High-elev accumulation zone.	yes	good
	Muir Glacier	Formerly tidewater glacier with spectacular retreat history.	yes	excellent
KATM	Fourpeaked Glacier	Valley glacier on an active volcano. Remote.	no	poor
	Knife Creek Glaciers	Unusual tephra-covered glacier with long historic record.	yes	good
KEFJ	Aialik Glacier	Tidewater glacier with historically stable terminus position.	no	moderate
	Exit Glacier	Tourist-popular, tidewater. On coastal side of Harding Icefield.	yes	excellent
	Skilak Glacier	Backcountry glacier draining interior side of Harding Icefield.	no	moderate
KLGO	Nourse Glacier	Outside park; moraine-dammed threatens infrastructure.	no	moderate
LACL	Tanaina Glacier	On flightseeing route at Lake Clark Pass. Changing hydroogy.	yes	moderate
	Turquoise Glacier	Cirque glacier with simple geometry. Remote.	no	good
	Tuxedni Glacier	Valley glacier on an active volcano. Remote.	yes	moderate
WRST	Bagley Icefield	Huge icefield with multiple distributaries. Remote.	yes	good
	Kennicott Glacier	Highly visited, tourist-friendly valley glacier. Jokulhlaup history.	yes	excellent
	Yahtse Glacier	Tidewater glacier that is currently advancing.	yes	good

Fieldwork, Resource Collection, and Development of Vignettes

In summer 2011, PI Loso visited several NPS units to collect existing resource materials and develop first-hand familiarity with some of the focus glaciers. The diverse historic and contemporary reference materials necessary for development of the focus glacier vignettes cannot be found solely through traditional library and internet resources; many resources are available only from NPS/NPS-affiliated personnel at AKRO and at the individual parks. It is therefore desirable to visit each park in person to meet directly with key personnel and browse NPS resources on file at those locations. Collected materials include:

- Published, peer-reviewed journal articles
- Internal NPS (and occasionally other agency) reports
- Internal NPS unpublished data, when available
- Historic maps
- Satellite and aerial imagery
- Interviews with knowledgeable persons
- Original and historic photography

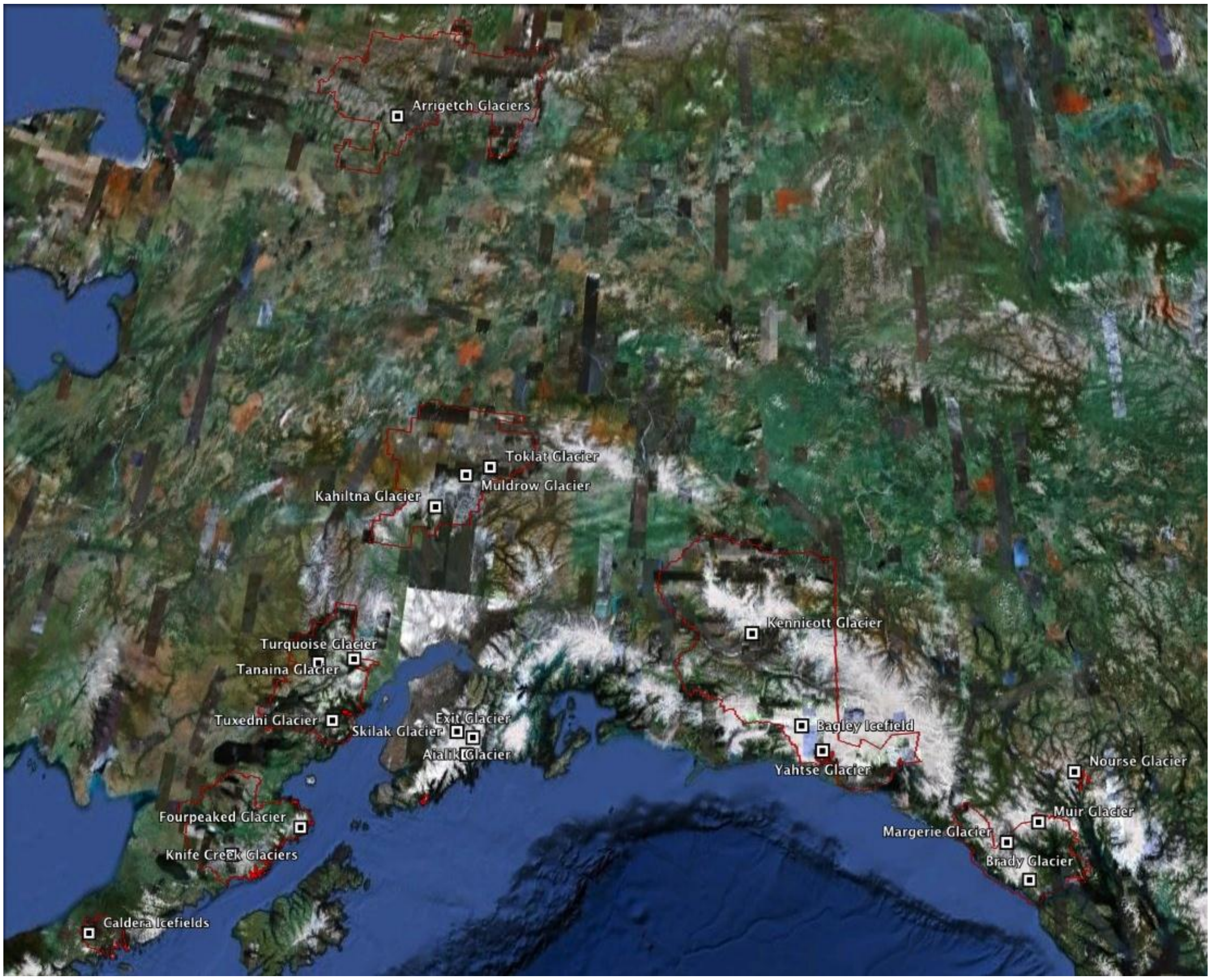


Figure 3. Overview of focus glacier locations. Base map courtesy Google Earth.

While on site at the various parks, Loso tried, within logistical and budgetary constraints, to personally visit as many focus glaciers as possible. These visits were not data-driven, but instead were conducted from the perspective of a science journalist. The objectives were to develop a first-hand familiarity with the field site geography, collect photographs (including, in some cases, repeat photographs of historic imagery), interview researchers and NPS staff working on or near each glacier, and qualitatively document the diverse evidence of landscape change.

Here, we summarize field efforts germane to the Glacier Bay vignette. Other fieldwork conducted in 2011 is beyond the scope of this progress report, and will be detailed in the March 30, 2012 deliverable (Table 2). Loso and one colleague, professional photographer JT Thomas, visited Glacier Bay between July 7 and July 16, 2011. Thomas served in a volunteer capacity, donating his time and making his images available for use in all publications associated with this project in exchange for travel expenses (covered out of Loso's travel budget under this agreement). From July 8-11, Loso and Thomas traveled by sea kayak up the East Arm to spend 3 days and 2 nights near the Muir Glacier terminus. From July 12-13, they traveled on the NPS research vessel Capelin up the West Arm to spend 2 days and 1 night near the Margerie / Grand Pacific Glacier termini, and on July 15, they traveled on the Capelin to Taylor Bay to spend a day near the Taylor Glacier terminus. On July 14 and 16, Loso visited park headquarters in Bartlett Cove to collect library and GIS resources (assisted by Rusty Yerxa and Bill Eichenlaub) and to interview local scientists (Lewis Sharman, Tania Lewis, Justin Smith, and Greg Streveler). Our work was conducted under a Scientific Research and Collecting Permit issued by Glacier Bay National Park and Preserve.

The target objective for each focus glacier is a vignette that uses text, photos, maps, and other information to highlight unique aspects of that glacier and ways that the glacier reflects broader trends in glacier change statewide. Most of these vignettes will be written during PI Loso's sabbatical year (fall 2012 – spring 2013). Until that time, the interim objectives for each focus glacier are to gather all available resources (as described above), to organize and digest those resources, and to identify the dominant themes for later presentation in vignettes. In this report we summarize progress on this synthetic process with an annotated resource list organized by the tentative interpretive themes for the focus glaciers.

Results-Mapping

Maps of glacier outlines, with associated geostatistics, were completed for all glaciers in Glacier Bay NP&P and Denali NP&P. In both cases, we expect to refine the datasets, particularly as we acquire additional, higher resolution imagery. We demonstrate the file structure envisioned for final data presentation in Figure 6, with more detail in Appendix C, but defer inclusion of the full datasets until the results are finalized. As with the other components of the project, our emphasis in this first phase of the project has been on project planning, development of methods, and acquisition of data. The analysis presented here is therefore focused on basic metrics of glacier change, but we ultimately plan a more robust analysis of the geostatistical component of the datasets (e.g. Bolch et al. 2010). Results for these two units are summarized sequentially below.

	A	B	K	L	M	N	O	P	Q	R	S	T	
1	ID	Name	B0	B50		B150	B200	B250	B300	B350	B400	B450	B500
359	G221630E59330N		0	1566	1070749	762211	430701	324723	344561	266252	290266	293921	
360	G221648E59280N		0	259465	202038	305406	428091	581055	494915	359701	380583	249024	
361	G221676E59266N		0	60559	20360	14096	10441	16184	10441	13052	46464	54294	
362	G221695E59255N		0	0	0	0	9397	7831	7831	10963	21405	49074	
363	G221713E59241N		0	0	16706	37588	14618	15662	22971	23493	49596	37588	
364	G221754E59212N		0	0	0	0	0	0	0	0	0	0	
365	G223300E58580N		0	0	0	0	0	0	0	0	0	0	
366	G223304E58588N		0	0	0	0	0	0	0	0	0	0	
367	G223323E58590N		0	0	0	0	0	0	0	0	0	0	
368	G223314E58593N		0	0	0	0	0	0	0	0	0	0	
369	G223216E58738N	Reid Glacier	303318	278781	380061	290789	501702	421304	536158	842608	908388	1954600	2
370	G223344E58602N		0	0	0	0	0	0	0	0	0	9397	
371	G223318E58620N		0	0	0	0	0	0	7831	24015	44375	129993	
372	G223400E58546N		0	0	0	0	0	28713	87184	146699	519974	232318	

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	ID	Name	Date	Code	Latitude	Longitude	Area	ElevMin	ElevMax	Mean	AWME	Kurowsky	Slope	SSTD	Aspect	ASTD
34	G224639E58591N		20100915	0	58.59120625	-135.3601285	0.253	1068	1353	1177	1178	1211	19.4	9.5	99.5	51.2
35	G224651E58591N		20100915	0	58.5913091	-135.3482893	0.366	788	1027	872	881	908	24.8	11.4	133.8	64.1
36	G224551E58608N		20100915	0	58.60844791	-135.4484441	0.482	1031	1341	1167	1171	1186	18.5	7.5	78.4	109.2
37	G222824E58855N	John Glacier	20100915	0	58.85541985	-137.1751105	1.853	851	1975	1280	1283	1413	21.9	10.4	88.6	52
38	G224616E58594N		20100915	0	58.59480555	-135.3832349	7.053	453	1369	890	890	911	18.4	10.3	195.4	131.4
39	G224625E58576N		20100915	0	58.57682955	-135.3740566	0.579	1084	1396	1217	1220	1240	16.5	8.5	111.9	82.5
40	G224650E58601N		20100915	0	58.60143293	-135.3495565	0.682	763	1201	962	964	982	19.5	8.7	138.5	138.6
41	G224151E58699N		20100915	0	58.69987092	-135.8483604	0.363	904	1139	1047	1043	1022	22.1	8.5	153.2	147.7
42	G224321E58674N		20100915	0	58.67489136	-135.6788249	1.246	999	1283	1163	1158	1141	14.8	8.1	255.8	87.8
43	G224554E58642N		20100915	0	58.64255128	-135.4458164	3.627	631	1501	1211	1211	1066	22.1	9.8	181.1	147.7
44	G224136E58708N		20100915	0	58.70804271	-135.8633572	0.681	995	1393	1224	1226	1194	24.5	8.3	68.6	88.1
45	G222880E58887N		20100915	0	58.88737309	-137.1199036	0.125	1251	1511	1384	1387	1381	23.7	9.8	164.7	34.9
46	G224334E58682N		20100915	0	58.68290559	-135.6651462	0.404	957	1261	1129	1128	1109	24.3	10.1	98.2	118.3
47	G222985E58875N		20100915	0	58.87533276	-137.0143299	0.205	883	1259	1063	1072	1071	30.6	11.6	293.1	54.3

Figure 6. Screenshots of sample data from Glacier Bay showing spreadsheet structure for hypsometry (above) and geostatistics (below). Hypsometry sheet shows elevation bins to 500 m, but continues to highest glacier elevations

Glacier Bay NP&P

Mapped outlines for Glacier Bay NP&P are shown in Figure 7 and summarized in Table 6. In total, Glacier Bay had 1120 glacier in 1952 (including those shared partly with Canada) and 15% more in 2010. We tentatively estimate errors in glacier area to be approximately 10%, but the sources of error have not yet been rigorously quantified. We expect errors to diminish as we utilize higher quality imagery, and we will present a thorough error analysis in the final report. However total ice-covered area decreased over that time interval by 11%, from a high of 7106 km^2 in 1952. Estimated total ice volume decreased a similar amount (13%), as would be expected since volumes are here calculated simply by scaling known area changes (Bahr 1997; Radic and Hock 2010). As implied by the overall area changes, terminus retreat was the response seen in most individual glaciers, including notable retreats by Grand Plateau, Desolation, Geikie, Casement, McBride, Burroughs, Plateau, and Muir Glaciers (Figure 7). A few glaciers advanced, too, including significant expansions by Grand Pacific, Johns Hopkins, Lamplugh, Rendu, and North Crillon Glaciers.

These overall changes in area are summarized on a per-glacier basis in Figure 8. Ranking glaciers by size (right panel), small to medium-sized glaciers increased in abundance over time while abundance of large glaciers was mostly unchanged. Ranking them by area-weighted mean elevation (left panel), low-elevation glaciers diminished in abundance while mid to high-elevation glaciers became more common. This increase in abundance of small, high-elevation glaciers is partly caused by breakup of larger glaciers into multiple, smaller tributaries. It is also true, however, that the resolution of satellite imagery is different than that of the aerial photography used by the USGS mappers, and consequent differences in the resolvability of small glaciers are also a factor.

The pattern shown in Figure 8 highlights the difficulty of using glacier numbers (as opposed to cumulative changes in total area or volume) as a reliable metric of overall glacier change. Cumulative changes in total area of glaciers, by elevation bin, are shown in Figure 9 and probably best reflect the overall change in glaciers in the Park. Above 2000 m, absolute changes in glacier area overall are small, while below 2000 m reductions dominate and are substantial. Relative to their small areas, however, the higher and lower elevations do show substantial percent changes from their 1952 coverages (Figure 10). Whether these small but proportionately important changes in ice coverage at high and low elevations are important is a question that a rigorous error analysis, which we have not yet completed, may help to answer. In the short term, the small absolute values of those changes, coupled with the noisiness of the data, cautions against over-interpretation of that particular result.

Table 6. Summary statistics for glaciers in Glacier Bay NP&P.

Time Period	Number of glaciers	Total glacier area (km^2)	Estimated volume (km^3)*
Map date (1952)	1120	7106	1729
Modern (2010)	1283	6427	1507
Absolute Change	163	-779	-222
Percent Change	15%	-11%	-13%

*volumes and volume changes are preliminary and subject to change. They are derived from area/volume scaling (Bahr, 1997) using exponent/coefficient values of 0.2055/1.375 from Radic and Hock (2010).

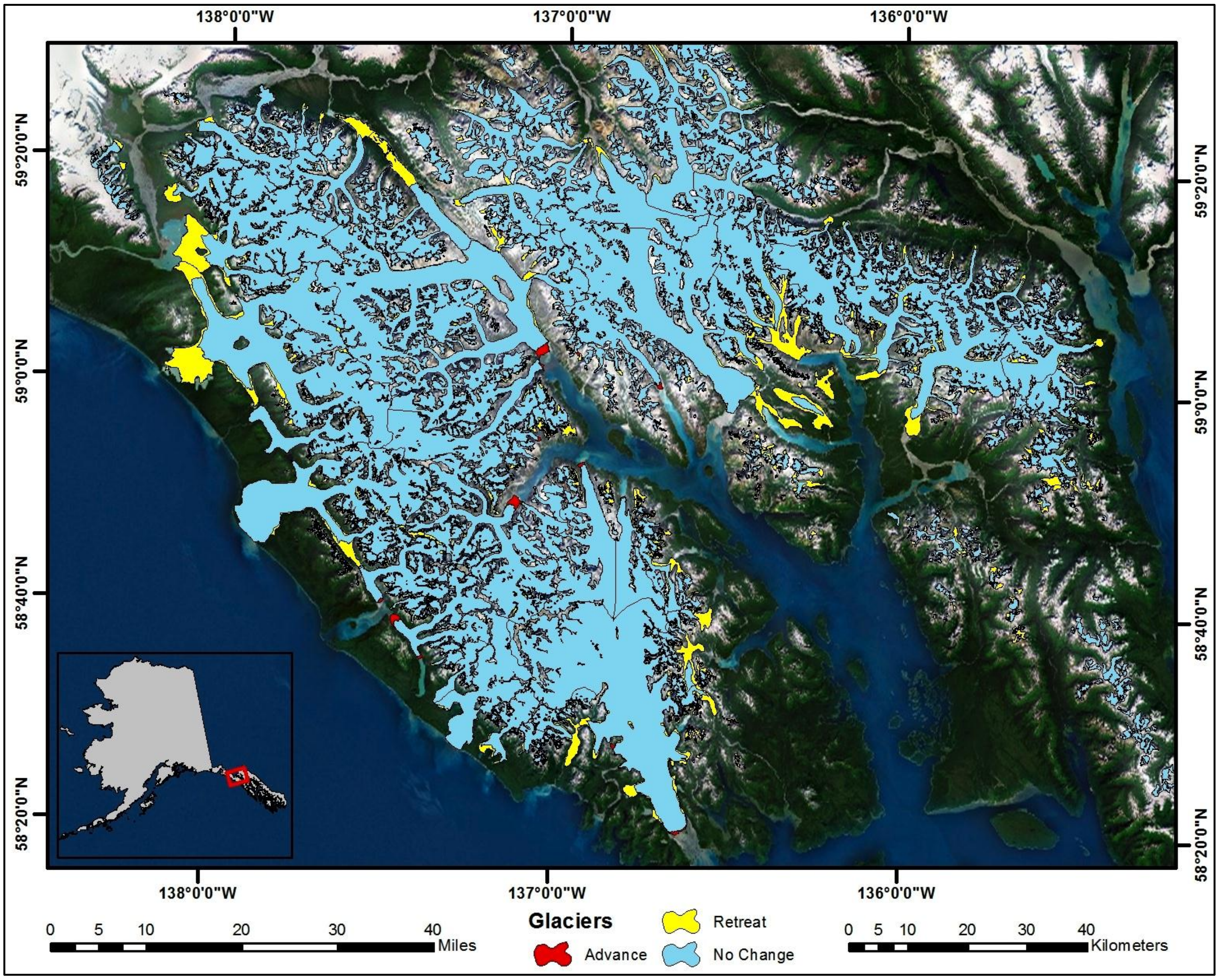


Figure 4. Changes in glacier area between the 1950s and 2000s in Glacier Bay NP&P.

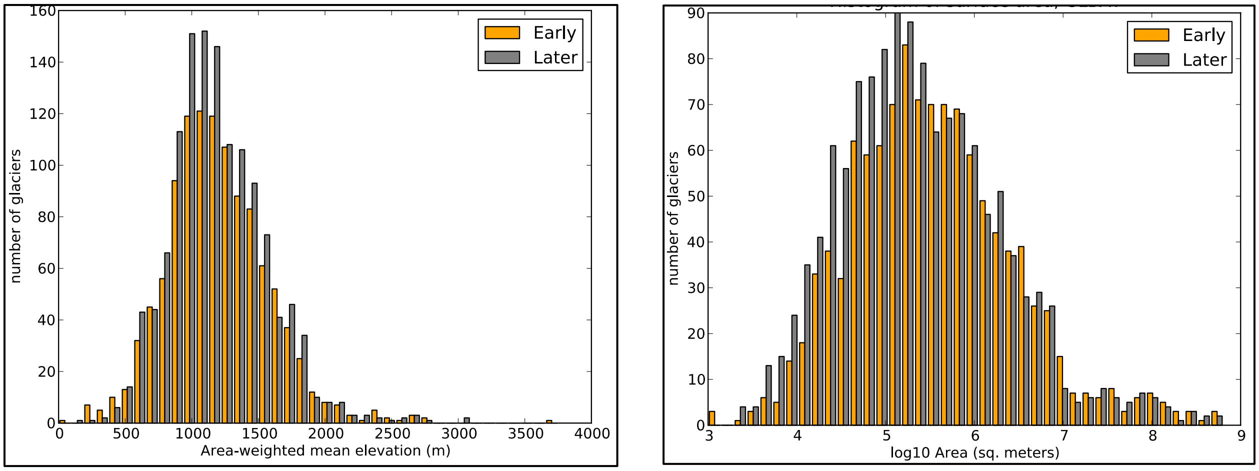


Figure 8. Histograms of changes in number of individual glaciers by area-weighted mean elevation (left) and area (right) in Glacier Bay between nominal dates 1952 ('early') and 2010 ('late').

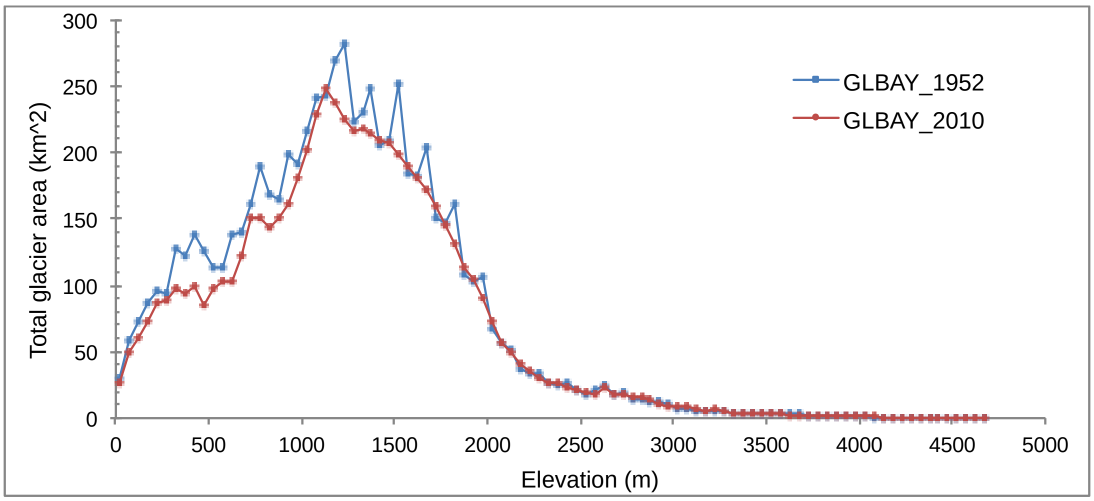


Figure 9. Total area of glacier-covered terrain in Glacier Bay by elevation between nominal dates 1952 and 2010.

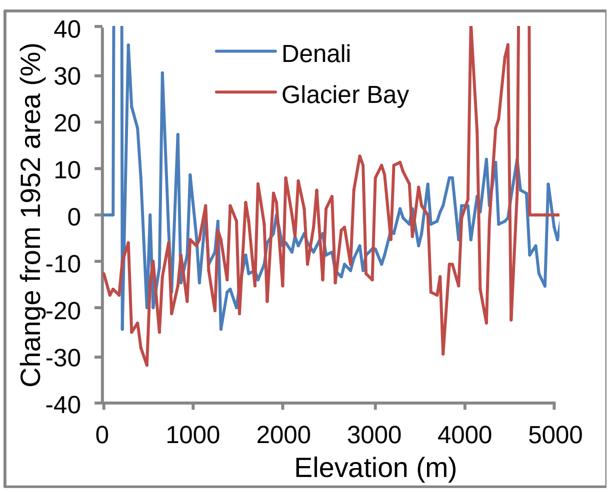


Figure 10. Percent change in glaciated area, by elevation, from 1952 to 2010 for Glacier Bay (red) and Denali (blue).

Denali NP&P

Mapped outlines for Denali NP&P are shown in Figure 11 and summarized in Table 7. In total, Denali had 1103 glacier in 1952 (very similar to Glacier Bay) and 23% fewer in 2010 (opposite in sign from Glacier Bay). Total ice-covered area decreased over that time interval by 8%, from a high of 4148 km^2 in 1952 (41% less ice cover at that time than that of Glacier Bay). Estimated total ice volume decreased 5%. As at Glacier Bay, terminus retreat was the type of change seen in most individual glaciers, but unlike Glacier Bay many of the glaciers in Denali, including most on the north side of the Alaska Range, are surge-type glaciers that periodically transport large amounts of accumulated mass from an upper reservoir area to the lower terminus area. Within the ~55 year time span documented here, the Muldrow and Peters Glaciers experienced surge events large enough to cause terminus advance (Figure 11).

These overall changes in area are summarized on a per-glacier basis in Figure 12. Ranking glaciers by size (right panel), small to medium-sized glaciers decreased in abundance or disappeared while abundance of large glaciers was mostly unchanged. Ranking them by area-weighted mean elevation (left panel), low-elevation glaciers diminished in abundance, mid-elevation (~2-3000 m AWME) glaciers did not change much in abundance, and high-elevation glaciers largely disappeared. This latter observation may be due to a variety of factors. Probably the main one is that there were a lot of small ice masses mapped by the USGS from aerial photography, which we did not map from Landsat due to poor quality imagery. In many areas the scene is saturated at high elevations, so rather than map blindly, we left it excluded glaciers in this area. Another reason may be these were mapped incorrectly by the USGS cartographers. Finally some of it is probably real change: small high-elevation ice masses disappearing faster than larger ones, possibly due to enhanced radiation from surrounding terrain. In any case, it is intriguing that this pattern is not seen in Glacier Bay's high elevation glaciers (Figure 8).

Cumulative changes in total area of glaciers, by elevation bin, are shown in Figure 13 and again are probably the best indicator of overall change in glaciers in the Park. Above 3000 m, absolute changes in glacier area overall are almost indistinguishable, and between 1800 and 3000 m glaciers lost a small area. The largest absolute loss of glacier area was between 1400 and 1800 m, and the pattern of change is mixed in sign and magnitude in the lowest elevations. Looking back at proportional changes in area by elevation in Figure 10, low elevation changes stand out. In particular, it is intriguing—in light of the surging behavior of many of Denali's glaciers—that many of the elevation bins below about 1400 m experienced growth in ice cover between 1952 and 2010.

Table 7. Summary statistics for glaciers in Denali NP&P

Time Period	Number of glaciers	Total glacier area (km^2)	Estimated volume (km^3)*
Map date (1952)	1103	4149	1051
Modern (2010)	754	3817	996
Absolute Change	-249	-332	-55
Percent Change	-23%	-8%	-5%

*volumes and volume changes are preliminary and subject to change. They are derived from area/volume scaling (Bahr, 1997) using exponent/coefficient values of 0.2055/1.375 from Radic and Hock (2010).

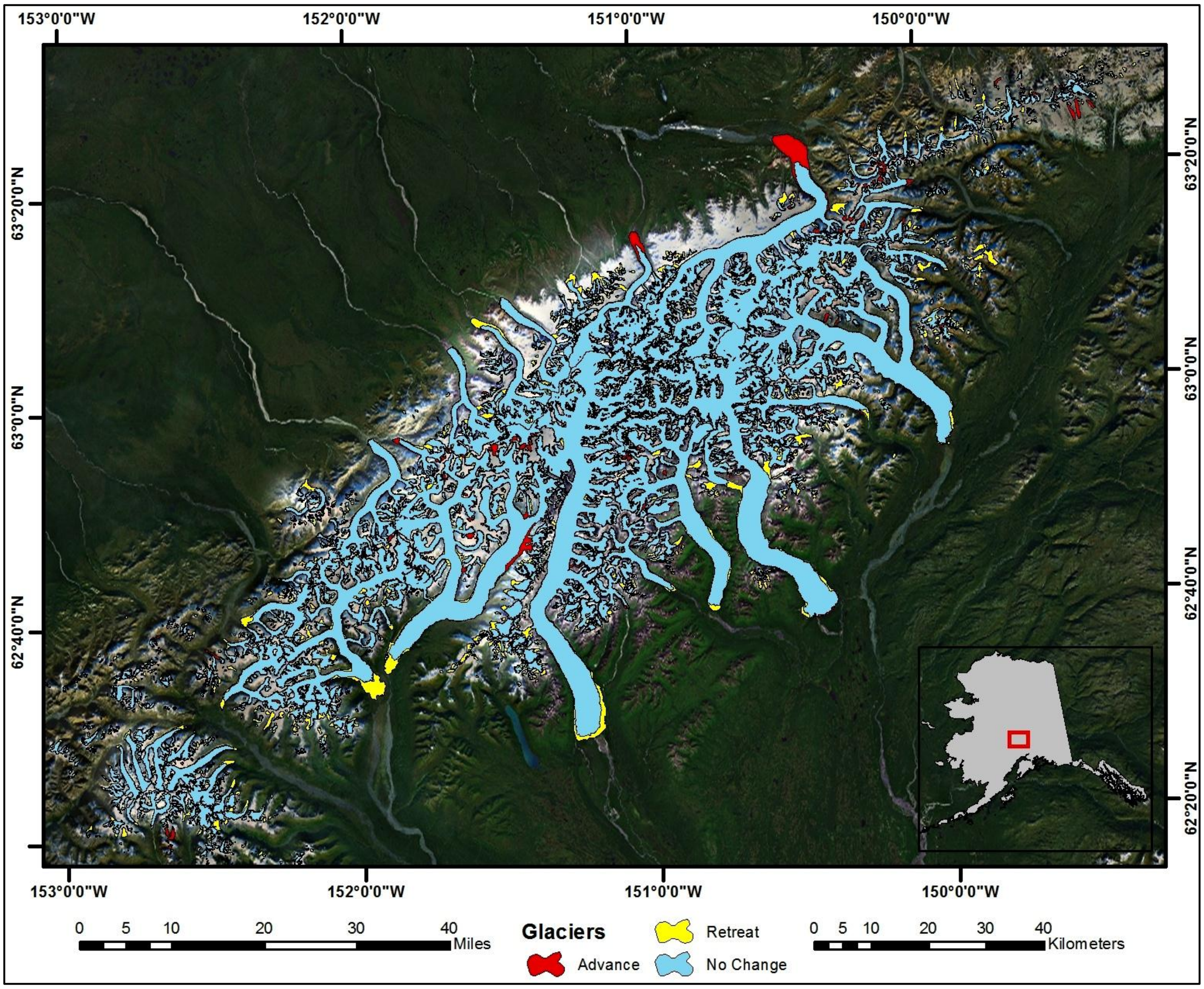


Figure 11. Changes in glacier area between the 1950s and 2000s in Denali NP&P.

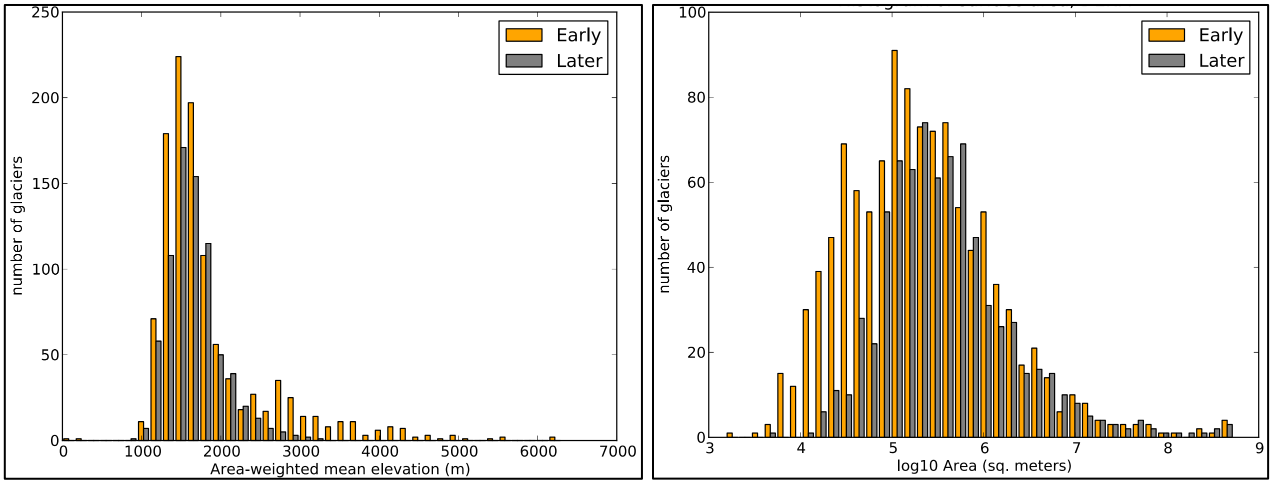


Figure 12. Histograms of changes in numbers of individual glaciers by area-weighted mean elevation (left) and area (right) in Denali between nominal dates 1952 ('early') and 2010 ('late').

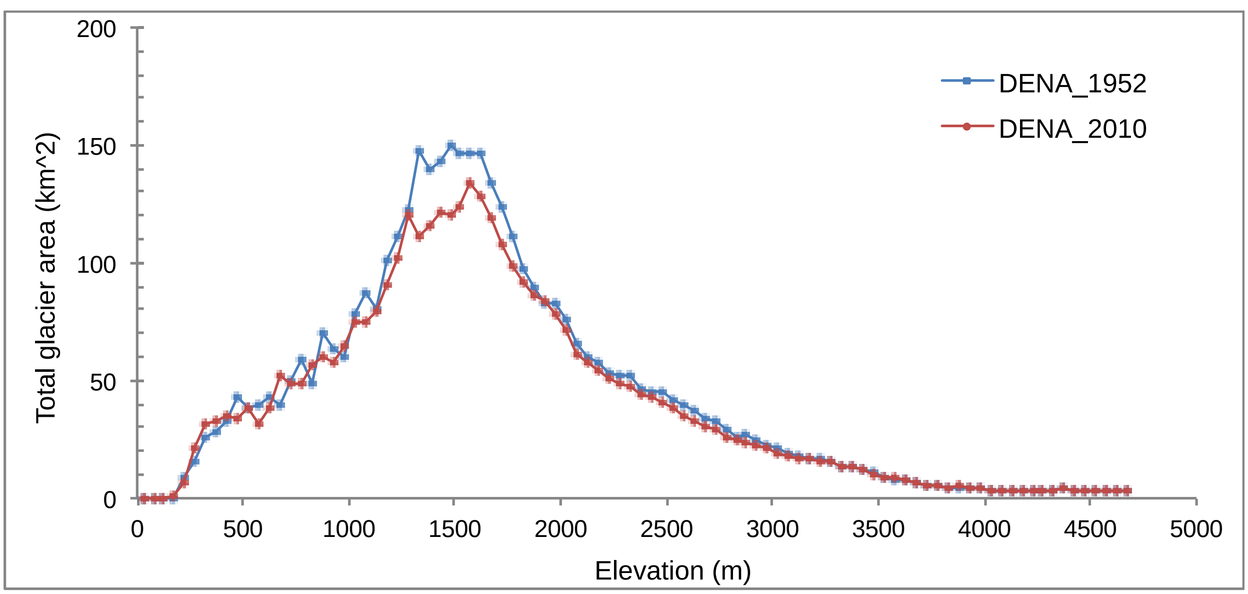


Figure 13. Total area of glacier-covered terrain in Denali by elevation between nominal dates 1952 and 2010.

Results-Elevation Change

We have completed analysis of surface elevation changes and inferred volume changes for sixteen glaciers in Glacier Bay NP&P over one to four intervals for each glacier, as shown in Table 4. Complete results for those thirty-two individual analyses are presented in Appendix A, but discussed here using the example of Muir Glacier over two time intervals between 2005 and 2011 (Figure 14). As shown there, Muir Glacier lost 0.061 (±0.008) km^3 ice each year from 2005 to 2009, and then 0.023 (±0.027) km^3 ice each year until 2011. But note that the 2005-2009 changes are based on far fewer matched data points than the 2009-2011 changes, and also that in both cases the changes at the highest elevations are not constrained by data but instead only by the necessity of elevation change tapering to zero at the upper edge of the glacier. Dashed lines in the elevation difference plots (e.g. Figure 14) show the upper quartile, median, and lower quartile values of all point-based change estimates in each 30 m elevation bin, excluding bins with fewer than 3 data points. Confidence intervals shown for volume change and glacier-wide mass balance rates are calculated by summing, across all bins, the differences between the fitted piecewise polynomial function and either the upper or lower quartile value (whichever is more different from the polynomial). Note that this calculation, as currently formulated, omits all bins with insufficient data for calculation of quartiles, and as such underestimates the confidence intervals for glaciers/intervals with the sparsest data. It is presently based only on the variability of the measured data, and we are continuing to work on the best method for calculating confidence intervals that also account for measurement errors, so the intervals presented here should be considered highly tentative.

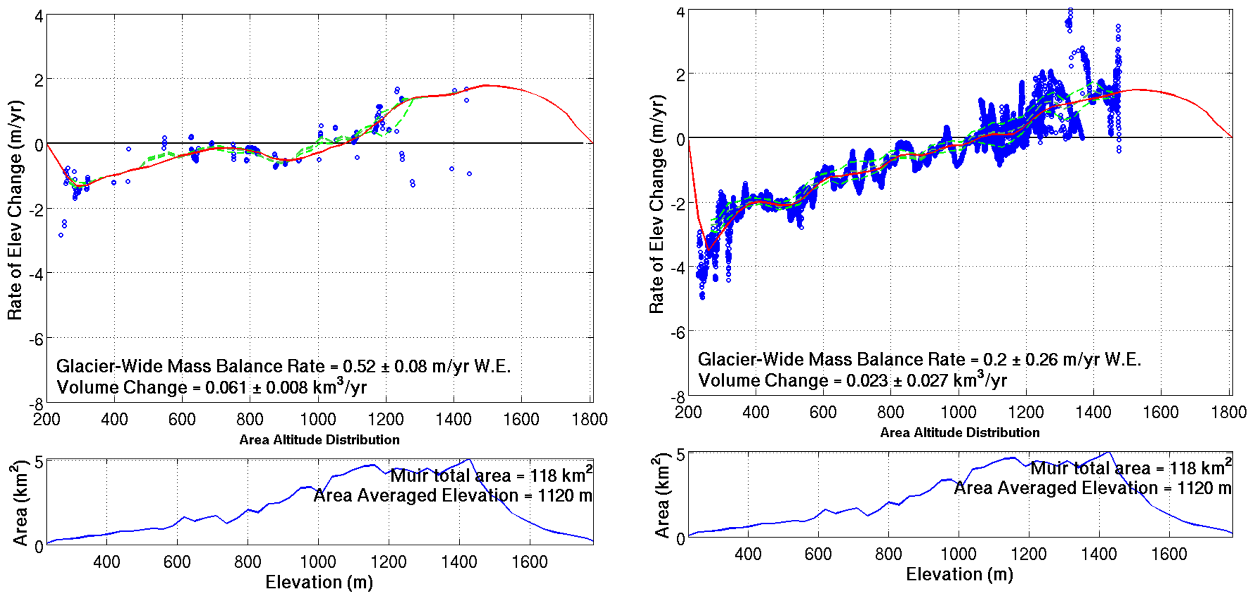


Figure 14. Elevation difference results (above) and area altitude distributions (below) from Muir Glacier during two time periods: 2005-2009 (left) and 2009-2011 (right). In upper plots, blue points are derived from raw laser point data, red lines are fitted piecewise polynomial functions, and dashed lines represent median, upper, and lower quartile values of differences in each 30 m elevation bin. Dashed lines are absent in bins with fewer than 3 overlapping laser points. See text for details.

Glacier-wide mass balance rates provide the most direct way of comparing volume changes on glaciers of different size, and a compilation of such values from all our data, showing the predominance of negative balances, is shown in Figure 15. The majority of glaciers sampled between 1995 and 2011 exhibited negative glacier-wide balance rates between 0 and -1 m/yr w.e. Averages for each time interval are not plotted, and should be interpreted with caution since the glacier coverage varies substantially from one interval to the next, but for the most commonly used intervals they are -0.6 m/yr w.e. (1995-2000), -0.9 m/yr w.e. (2000-2005), -0.4 m/yr w.e. (2005-2009), and -0.6 m/yr w.e. (2009-2011). On a glacier-by-glacier basis, Grand Pacific Glacier had the most negative glacier-wide balance between 2001 and 2009 (-2.0 m/yr w.e.) and Margerie had the most positive glacier-wide balance between 2009 and 2011 (+0.5 m/yr w.e.). In the final document, it will be productive to review these results in comparison with the longer (50 year) record of thinning documented for Glacier Bay in Larsen et al. (2007).

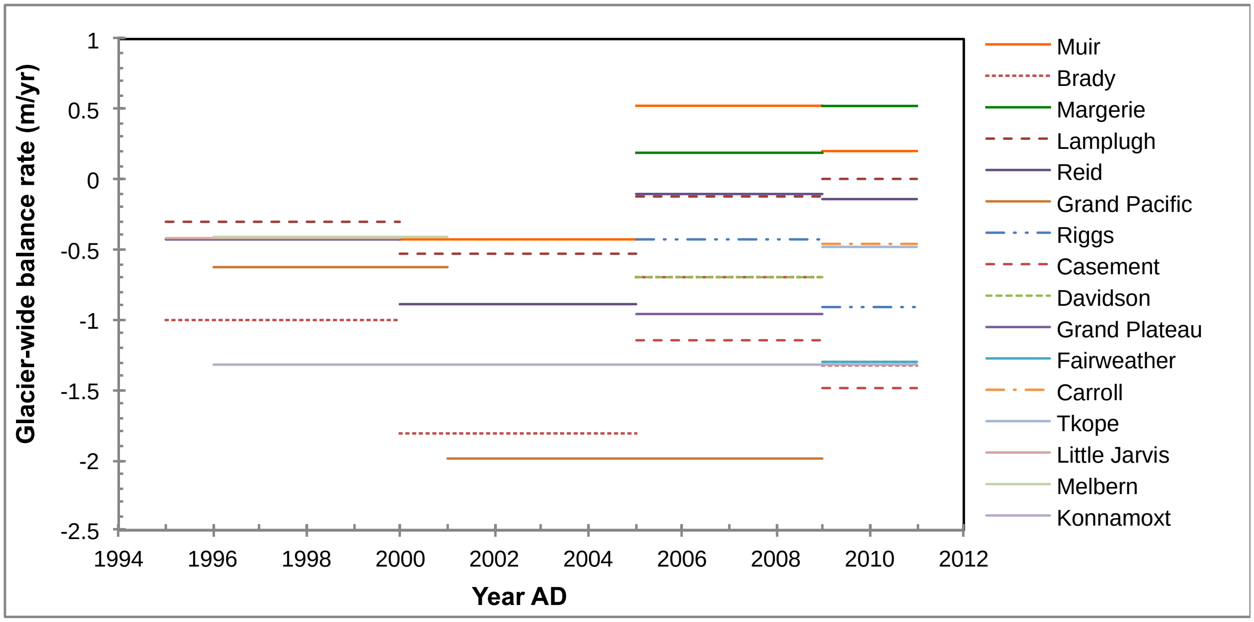


Figure 15. Glacier-wide mass balance rates (m/yr) for twelve glaciers from Glacier Bay NP&P over multiple time intervals between 1995 and 2012. Confidence intervals excluded for clarity. See appendix A and text for complete details.

Spatial and temporal trends in volume change, by elevation, are shown in Figure 16. Spatial coverage is sparsest during the early period, 1995-2000, and shows that volume loss (thinning) was greatest near the terminus of the Brady Glacier. Between 2000 and 2005, the pattern of thinning on Brady Icefield intensified, and we. We have data showing a complex mix of terminus thinning, mid-elevation thickening, and high elevation thinning on the Muir Glacier (which has a small positive glacier-wide mass balance rate during this period). From 2005 to 2009, terminus thinning on Brady diminished, and the highest rates of thinning were seen near the terminus of Casement Glacier and Grand Plateau Glacier. Thickening was seen during this period on upper Muir Glacier, lower Margerie Glacier (both of which had small positive glacier-wide mass balance rates during this time period), and in some higher elevations of the Fairweather Range. Spatial and temporal coverage of these plots will increase as we complete some final analyses of these data.

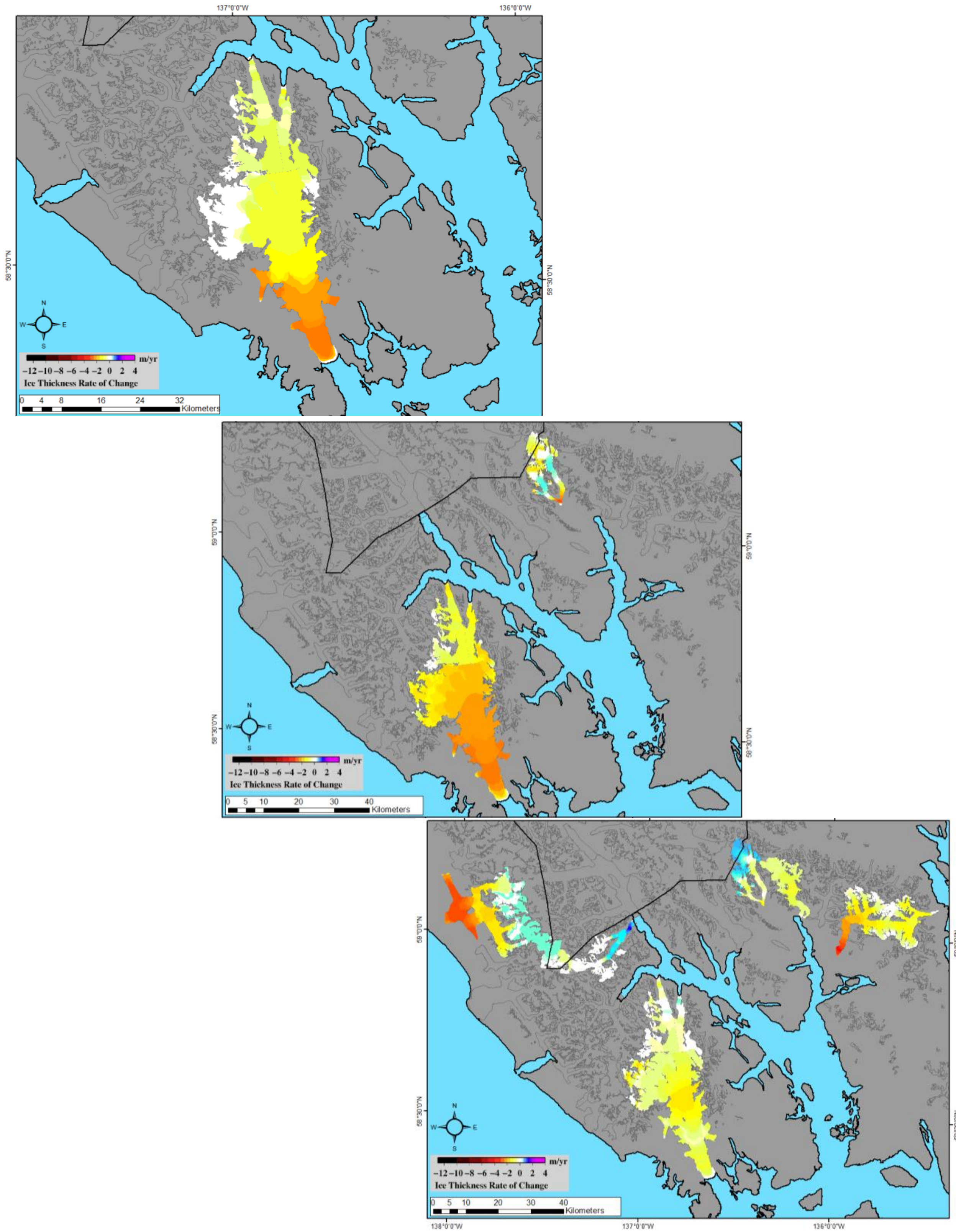


Figure 16. Annual rate of ice thickness change, by elevation, for selected glaciers in Glacier Bay National Park and Preserve between 1995 and 2000 (upper panel), 2000 and 2005 (middle), and 2005 and 2009 (lower).

Results-Focus Glaciers

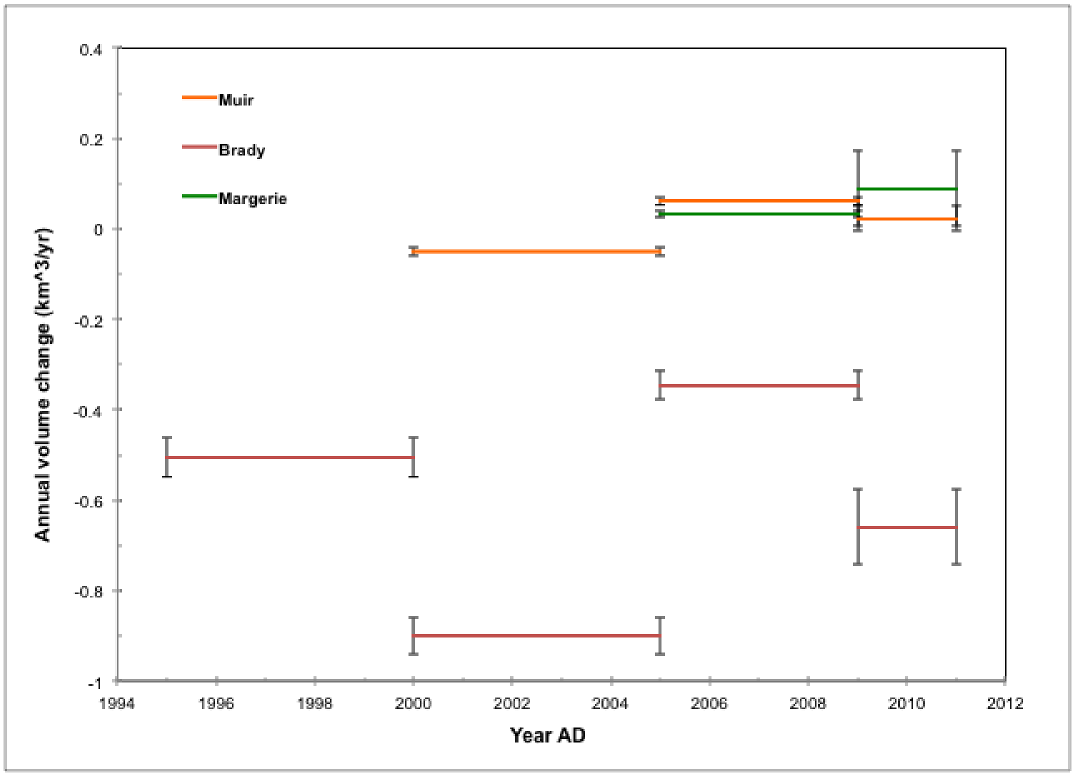
As described earlier, the focus glacier component of this project will culminate in creation of a narrative-based and graphic rich vignette for each glacier. These vignettes will primarily be completed during Loso's sabbatical year (fall 2012 – spring 2013), but a sample vignette will be constructed for Knife Creek Glacier (Katmai NP&P) to present (in poster form) at the upcoming National Park Service Southwest Alaska Science Symposium, November 2-4 2011 in Anchorage, AK. The abstract submitted for this presentation is included as Appendix B to this report. This presentation will provide an early opportunity for project collaborators and other interested NPS personnel to comment on the proposed format for the vignettes. For the purposes of this progress report, the emphasis is therefore on documenting results of the data gathering and synthesis portion of this work—rather than the writing.

Glacier Bay has an unusually rich history of glacier photography, and some of the repeat photographs from the park will be used in the vignettes. The archives at the park are vast but poorly indexed, and for our purposes the primary sources of photography will be Ron Karpilo's collection (Karpilo et al. 2007), Bruce Molnia's collection (NSIDC/WDC for Glaciology 2009), and historic photographs archived at the park. Similarly, we will rely on maps from historic work and park GIS staff to develop graphics for the final vignettes.

Creation of vignettes for some of the focus glaciers selected for this project will be challenged by the lack of contemporary and historic information about them. This is not the case for Glacier Bay—the glaciers of this park unit are arguably the best studied and best known in Alaska, and our visit to the park headquarters and library in Gustavus was engaging, productive, and slightly overwhelming in terms of the amount of information available. Given the limited scope of the vignettes, it is neither desirable nor practical to exhaustively summarize every available historic resource. The challenge has been to become familiar with all of these resources and to pick out the gems—those that document the most unique aspects of Glacier Bay's focus glaciers. Of the hundreds of documents, maps, and reports in the Glacier Bay library (not even counting the additional hundreds of historic photos), we summarize below those resources that seem to be most critical as sources of information about the focus glaciers. We welcome suggestions of additional resources not included in this section. The section is organized by narrative themes, corresponding to what we have judged to be the most critical themes for this particular park.

Glacier changes

Glacier Bay is home to the best-documented example of tidewater glacier retreat in historic time (though the Columbia Glacier is running a close second). The primary source of information about changes in the focus glaciers over recent decades will the datasets compiled by other components of this project. Glacier outlines and elevation changes shown in the broad context of the overall park can be shown in more detail for the Brady (Figure 18), Margerie (Figure 19), and Muir (Figure 20) Glaciers. Two examples are shown in Figure 14 and Figure 17. These recent changes, however, are minor in comparison with the changes since the 1700s, and fortunately these changes too are well documented. Many early geologists visited Glacier Bay (e.g. Baldwin 1892, Muir 1915) and their many works are well-synthesized by many later authors (Barclay et al. 2009; Molnia 2008) whose works supplement historic papers in depicting rates of glacier change. In addition to these general sources of information, for particular focus



glaciers we'll use the following references: Brady-Capps et al. 2011, Derksen 1976; Margerie-Hall et al. 1995, Hunter et al. 1996, Post 1969; Muir-Field 1980, Hunter et al. 1996.

Figure 17. Average annual rate of volume change for three focus glaciers in Glacier Bay National Park and Preserve for multi-year time intervals between 1995 and 2011. Error bars at either end of each interval are equal and give average error over the period of measurement.

Tidewater Glacier Cycle

From an interpretive standpoint, what is probably more important about Glacier Bay than its history of tremendous glacier retreat is the *cause* of that retreat. The entire *Status and Trends of NPS Glacier* project is being funded by climate change funding, and it is very important that the Glacier Bay focus glaciers be used to clarify the complicated and decidedly indirect relationship between tidewater glaciers and climate. That relationship has been addressed directly by Mann (1986), Hunter (1994), and others, but is fundamentally described in the literature on the tidewater glacier cycle, which was first described by Post (1975) and is being revised by a new article in press (Post et al. in press). We will use Glacier Bay's focus glacier to elucidate the big picture dynamics of tidewater glaciers, and will likely focus more on details of calving and fjord sedimentation dynamics when discussing Yahtse Glacier in WRST.

Sea level and isostasy

Sea level rise is a function of glacier melt everywhere, but the tremendous ice loss from Glacier Bay in recent centuries has made a disproportionately large contribution. Even more compelling, the rapid loss of ice mass from the Bay has resulted in globally distinctive rates of isostatic uplift, complicating the local history of relative sea level change and providing an excellent opportunity to educate visitors about the role of glaciers in sea level rise (and fall). Primary resources are Larsen et al. (2005, 2007), Mann and Streveler (2008), and Motyka et al. (2007).

Succession

Glacier Bay, with its rapid historical glacier retreat and early visibility to the scientific community, has historically been perhaps the single-best studied laboratory of primary succession in the world. Many, many articles have been written about the pattern of soil and terrestrial vegetation development there, and so it makes sense to focus on succession as a primary theme for development at Glacier Bay, even though succession is clearly occurring at focus glaciers throughout the state. Key references for terrestrial vegetation succession are the landmark paper by Chapin et al. (1994) and the influential paper on differing pathways of succession by Fastie (1995). Milner et al. (2000) studied succession in stream communities. Less attention has been given to the nature of marine succession at the terminus of tidewater glaciers, but here again Glacier Bay is at the forefront because of work by Lewis Sharman (Sharman 1987, 1991). A great paper synthesizing the linkages among these ecosystem developments was co-authored by many of the scientists working on the aforementioned works (Milner et al. 2007).

Effects on wildlife

Effects of glacier change on animals are poorly documented in most areas, but Glacier Bay is again at the forefront of this sort of research. Perhaps most prominent among the glacier-loving creatures at Glacier Bay (though also present at Aialik Bay, another focus glacier in KNFJ) are the harbor seals. Numbers of harbor seals, which have been declining in GLBA, are described by Bengtson et al. (2007), and the ways that seals interact with glacier ice are addressed most recently by Womble et al. (2010). The “Glacier Murrelet” (Kittlitz Murrelet) has critical populations in Glacier Bay and Icy Bay, and their relationship to glaciers is described by Arimitsu (2009). The Black-Legged Kittiwake colony at Margerie Glacier is a conspicuous attraction for cruise ship passengers (Heacox 1983) but we’d like to find better documentation of this colony’s relationship to the glacier. Even more speculatively, GLBA wildlife biologist Tania Lewis (pers, comm. 2011) studies bears and has made observations of bear density and vegetation type that suggest grizzly bears utilize the West Arm of Glacier Bay more than the East Arm because of differences in how plants have colonized the two arms after deglaciation, due perhaps to the closer connection of the West Arm to inland sources of plant propagules (from the Alsek River via the Grand Pacific and Melbern Glaciers).

Cultural ethnography

The response of the Huna Tlingit people of Glacier Bay to the glacier fluctuations therein, and particularly to the rapid retreat of glacier ice from the Bay after the Little Ice Age, is important and well-documented by Connor et al. (2009) and references therein. A more general, but compelling, look at the relationship between traditional people, modern scientists, and glacier change is based on stories from the Glacier Bay region and will also be used (Cruikshank 2001).

Figure 18. Brady Glacier terminus and Taylor Bay in the foreground. Glacier Bay NP&P Summer 2006. Denny Capps photo.

Figure 19. Margerie Glacier terminus with characteristic visitors. Glacier Bay NP&P July 12, 2011. JT Thomas photo.

Figure 20. Muir Glacier terminus (right) and the tributary Morse Glacier (left) as seen from the East Arm of Glacier Bay. Glacier Bay NP&P July 10, 2011. JT Thomas photo

Discussion

Preliminary highlights

The work presented here is preliminary, and our main intention has been to document our approach to the project, our success in collecting and analyzing the first datasets, and our intentions for the remainder of the project. Analyses presented herein are tentative, and will be emphasized over raw data in the final report. Nonetheless, some trends emerge from our preliminary work.

- Glacier Bay National Park and Preserve was 53.5% glaciated in 1952, but ice cover diminished 11% by 2010, to become 48.4% glaciated (6427 km^2).
- Denali National Park and Preserve was 16.9% glaciated in 1952, but ice cover diminished 8% by 2010, to become 15.5% glaciated (3817 km^2).
- The vast majority of glaciers in both parks have shrunk considerably, mainly by terminus retreat, in that time.
- A few glacier termini advanced in Glacier Bay since 1952. All these advances are by tidewater or recently-tidewater glaciers in retracted positions that may indicate a resumption of normal tidewater glacier expansion.
- Only two significant glacier expansions occurred in Denali since 1952. Both were surge-type glaciers: Muldrow and Peters Glaciers. Some smaller expansions were found.
- Using laser altimetry, we measured 32 distinct intervals of elevation change distributed among sixteen glaciers in Glacier Bay between 1995 and 2011. Of these measured intervals, all had negative glacier-wide mass balance rates (overall thinning) with five exceptions: positive rates on Muir Glacier 2005-2009 and 2009-2011 and Margerie Glacier 2005-2009, 2009-2011, and one neutral interval (Lamplugh Glacier 2009-2011).
- The lowest measured balance rate (greatest thinning) was on Grand Pacific Glacier from 2001-2009: ice loss average 1.99 m/yr over the entire glacier surface.
- We visited eleven of the 20 selected focus glaciers in summer 2011, including all three of the Glacier Bay focus glaciers: Brady, Margerie, and Muir. NPS personnel at many parks were extremely helpful in facilitating the visits and sharing information.

Challenges

We are early in this multi-year project, on schedule, and optimistic about the final products. There are, however, some challenges and questions emerging thus far in the project. None are overwhelming, but at this early stage it seems productive to identify some of these challenges while the entire group has an opportunity to address them. Our goal in including them here is to open a discussion about these items. We itemize these challenges below, in no particular order.

- An ongoing challenge for the mapping component of the project has been the lack of high-resolution imagery necessary to accurately delineate glacier boundaries. We have thus far been working primarily with Landsat data, but would like to refine some boundaries with higher-resolution commercial imagery. This is a particular problem in regions with extensive debris cover, where multispectral mapping is unable to discriminate between bedrock and debris on glacier surfaces, and in distinguishing smaller ice masses. We are working closely with GINA to stay informed about any new imagery made available through the recent Alaska mapping initiative. It would be extremely helpful if NPS could provide any available commercial imagery they have (some of which was identified and/or promised in our early meetings) so that we can improve the quality our deliverables. Designation of a qualified NPS "go to" person for this item would be a helpful first step.

- Spatial data formatting. We have not presented any raw spatial data with this project report, but complete spatial data are an important component of our final deliverable. There has already been some discussion of the best format for organizing and presenting this data to NPS. Issues include which datum and projection to use, what digital formats to use, how to integrate this with existing NPS data, and the timeline for presentation of data to NPS/GLIMS/NSIDC. As with the previous item, it would be helpful to identify a point-person in the NPS GIS shop to work with on this.
- As a trivial item, we have had to decide what to do about glaciers that are partially within a park's boundaries. Our tentative decision has been to include, in their entirety, all glaciers that are at least partly inside a park unit. This overstates glacier coverage in the parks, however. Is NPS comfortable with this decision?
- Another minor issue for the mapping component has been determining the best method to track changes in area of individual ice masses. Labels for ice masses are based on the location of the polygon centroid, which changes over time. Additionally, ice masses often split during glacier retreat, so that one ice mass becomes two. Less often, they merge. In this way, tracking individual masses and total numbers of glaciers is both problematic and can be deceiving. The challenge can be visualized in Figure 21. We would enjoy discussing the best approach to this with NPS personnel.
- The focus glacier work is predicated on existence of a body of historic/contemporary work that allows us to summarize a given glacier's history without substantial additional fieldwork. Based on our experience this summer, that task for most focus glaciers will be very reasonable. But we would like to draw attention to a few focus glaciers about which we are aware of very little historical literature of any sort: the Aniakchak Caldera icefields and the Fourpeaked Glacier. To a lesser extent (because a little more material is available) we are also concerned about resources for Skilak Glacier and Tuxedni Glacier. Our concern here is that we fundamentally have very little to say about these glaciers. Alternatives include leaving those glaciers out of the final report, being made aware of existing resources we have not yet found, or mounting a modest research campaign to generate new data about these glaciers. We are open to any of these, but would like to discuss this with our collaborators.

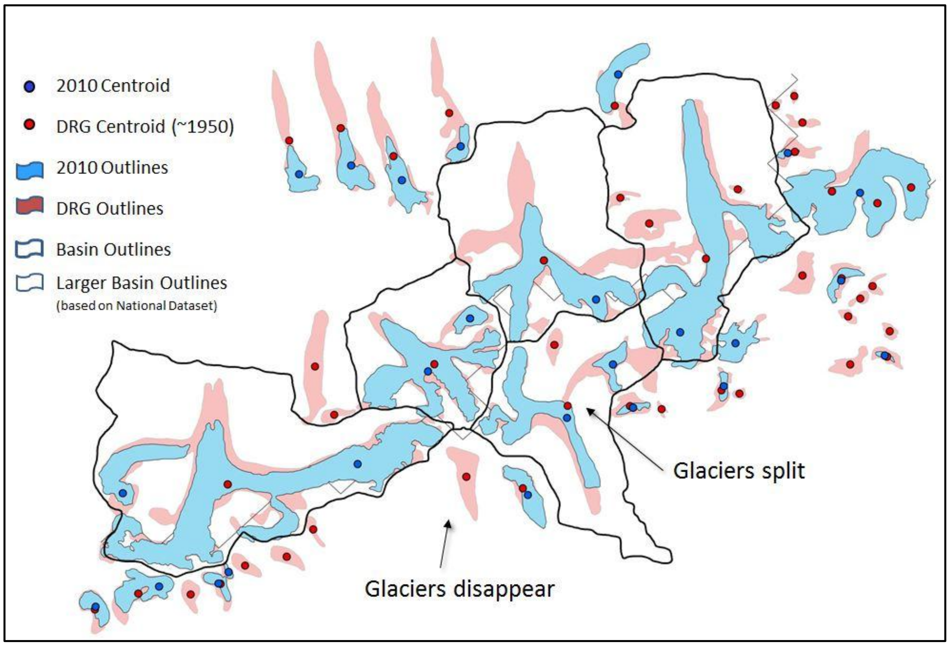


Figure 21. Individual glaciers are labeled according to a point located at the centroid of the polygon. When a glacier retreats and splits into two different glaciers, it receives a different label and so is no longer possible to track the evolution of that single glacier through time. A similar problem occurs when two glaciers advance and merge into one. Examples of both are shown here.

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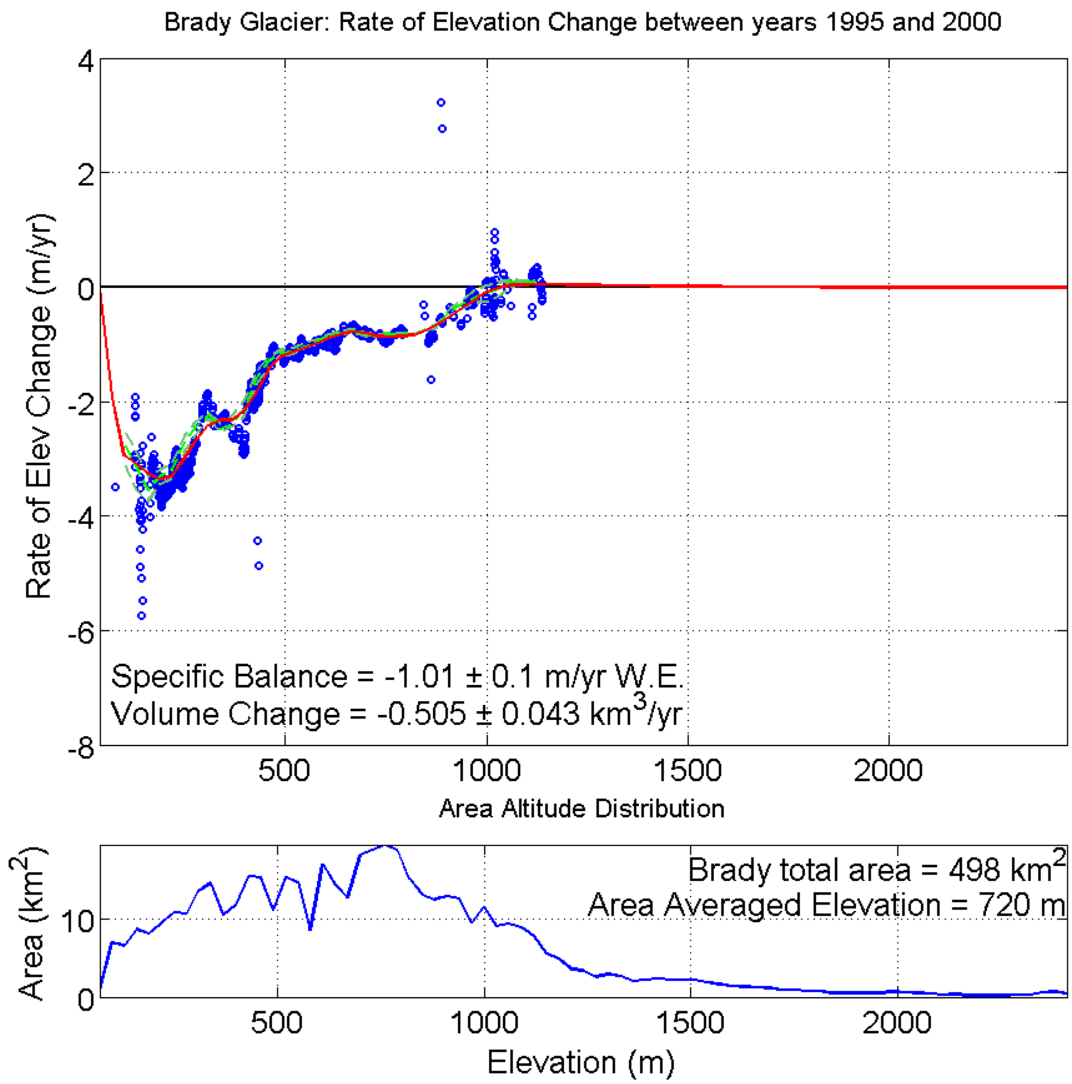
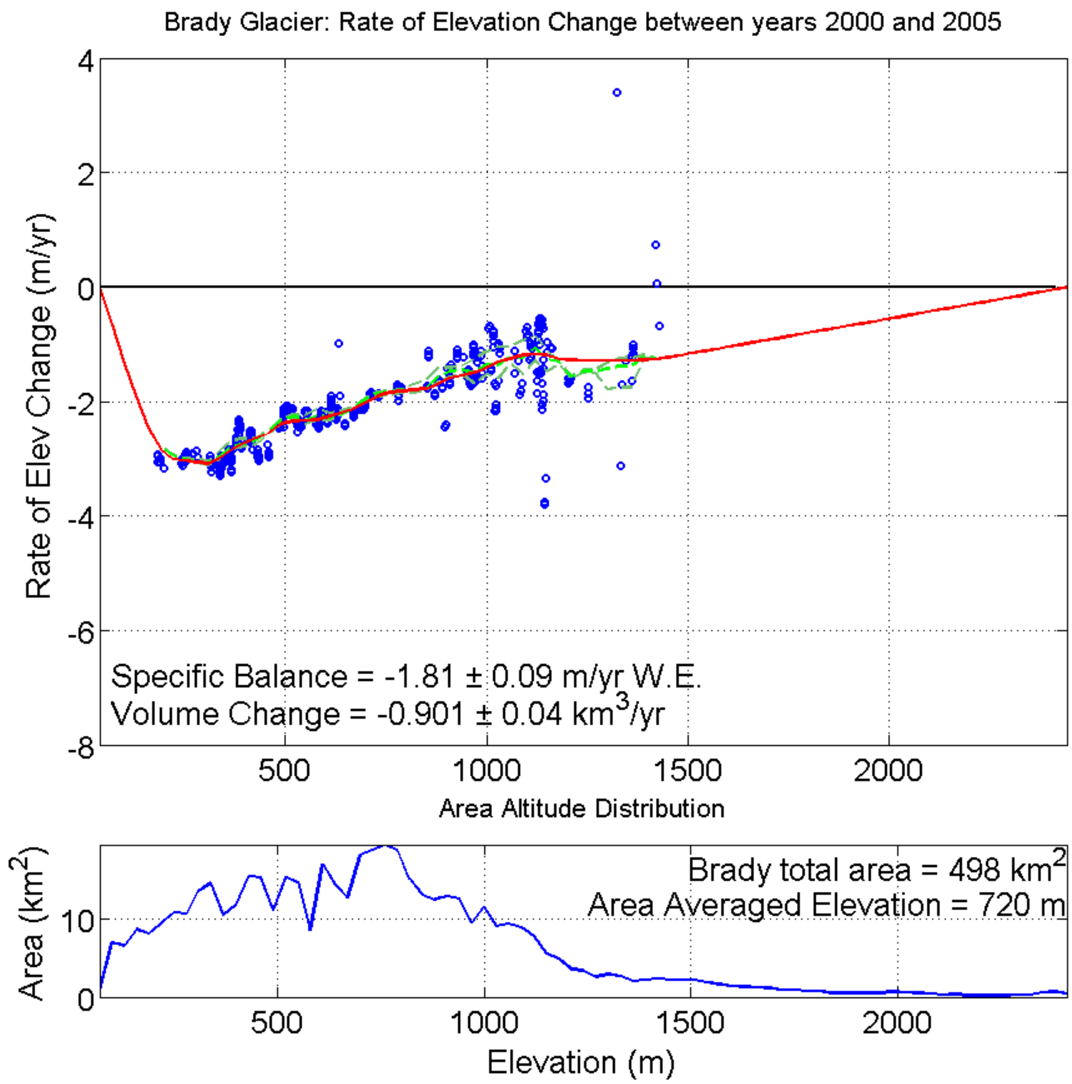
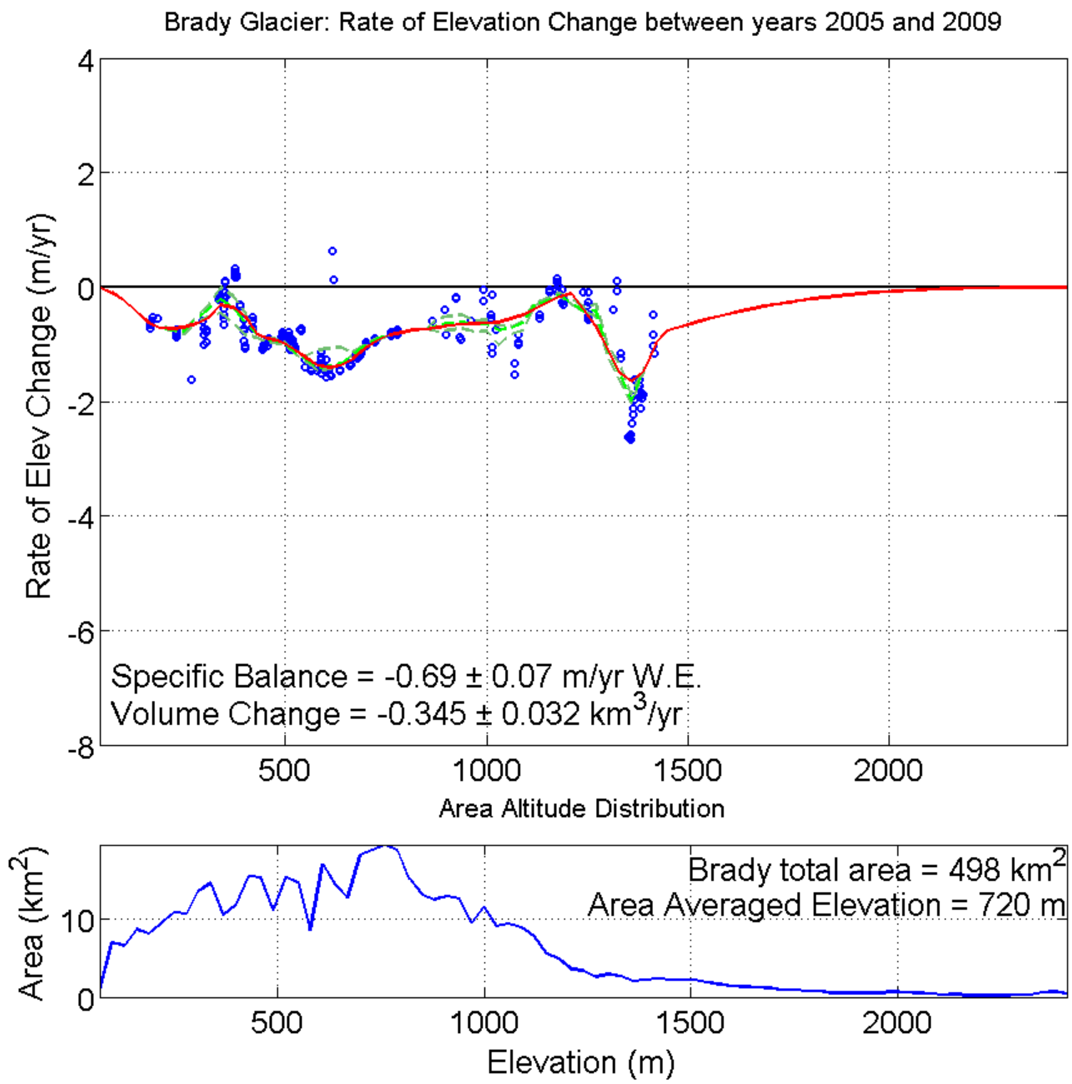
Appendix A: Elevation and Volume Change Analyses

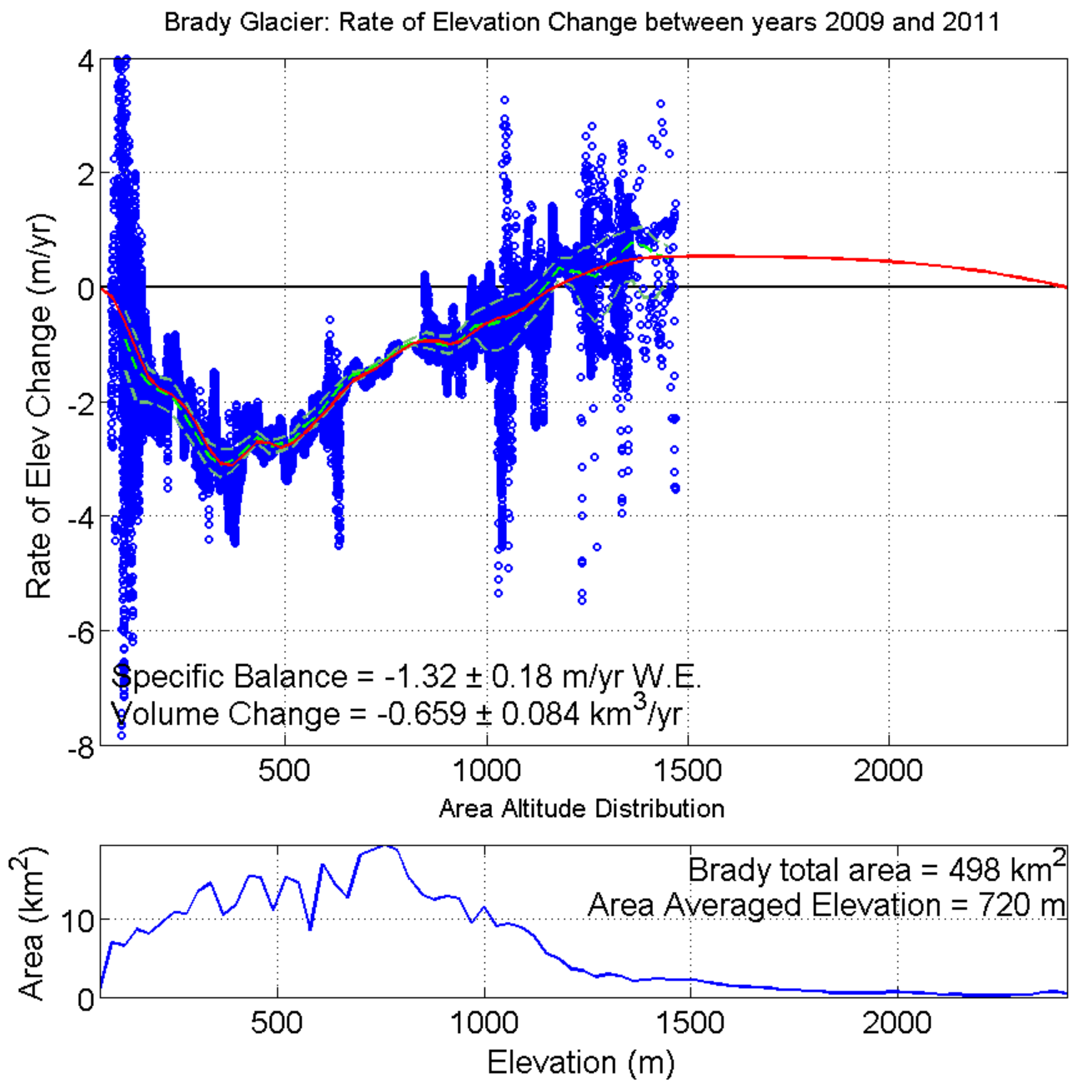
Note that the "Specific Balance" on these plots is identical to the "Glacier Wide Mass Balance Rate" as described in the text. The latter term will be used exclusively in subsequent reports.


Brady Glacier: Rate of Elevation Change between years 1995 and 2000
Rate of Elev Change (m/yr)
4
2
0
-2
-4
-6
-8
500
1000
1500
2000
Specific Balance = -1.01 ± 0.1 m/yr W.E.
Volume Change = -0.505 ± 0.043 km^3/yr
Area Altitude Distribution
Area (km^2)
10
0
Brady total area = 498 km^2
Area Averaged Elevation = 720 m
500
1000
1500
2000
Elevation (m)

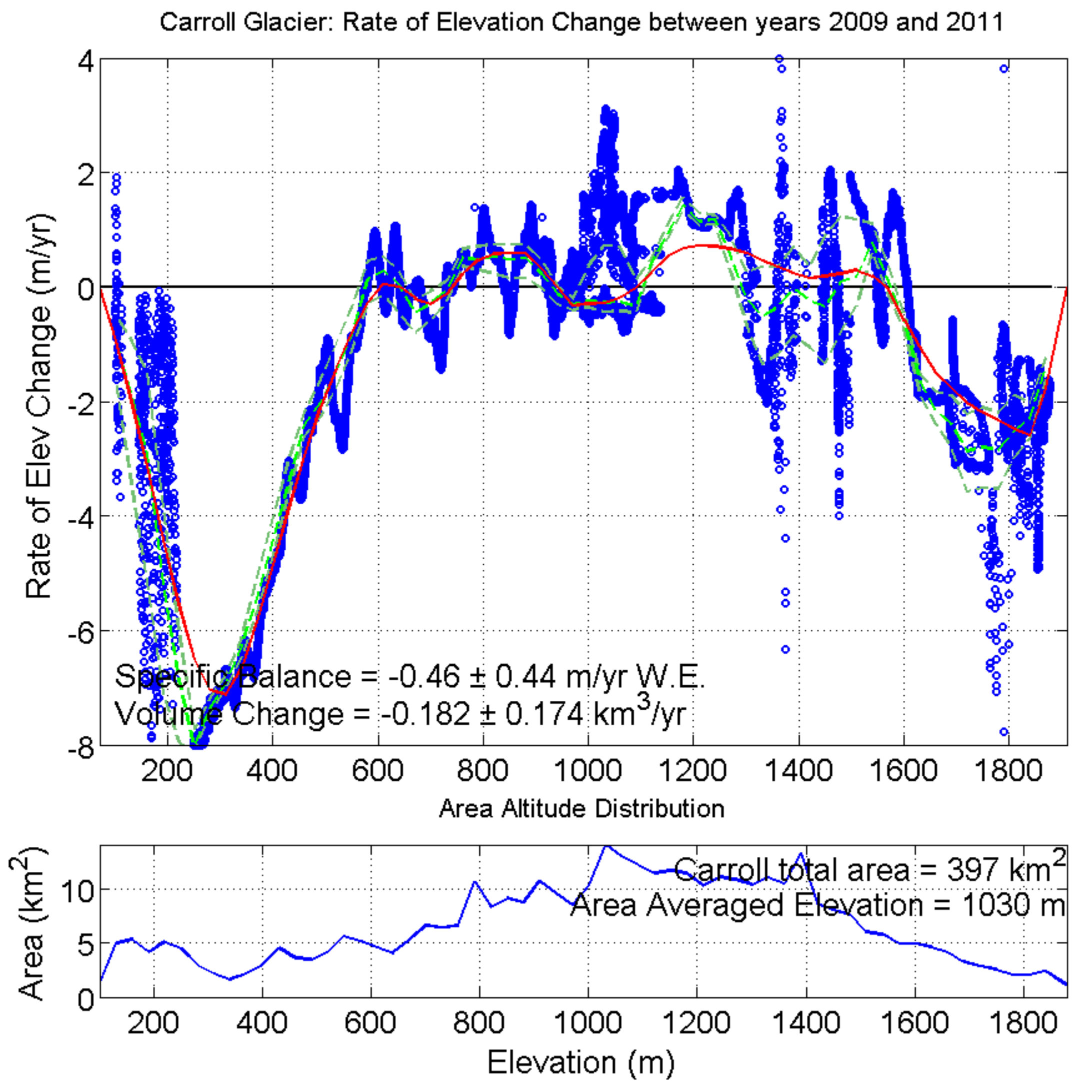

Brady Glacier: Rate of Elevation Change between years 2000 and 2005
Rate of Elev Change (m/yr)
4
2
0
-2
-4
-6
-8
500
1000
1500
2000
Specific Balance = -1.81 ± 0.09 m/yr W.E.
Volume Change = -0.901 ± 0.04 km3/yr
Area Altitude Distribution
Area (km2)
Brady total area = 498 km2
Area Averaged Elevation = 720 m
10
0
500
1000
1500
2000
Elevation (m)



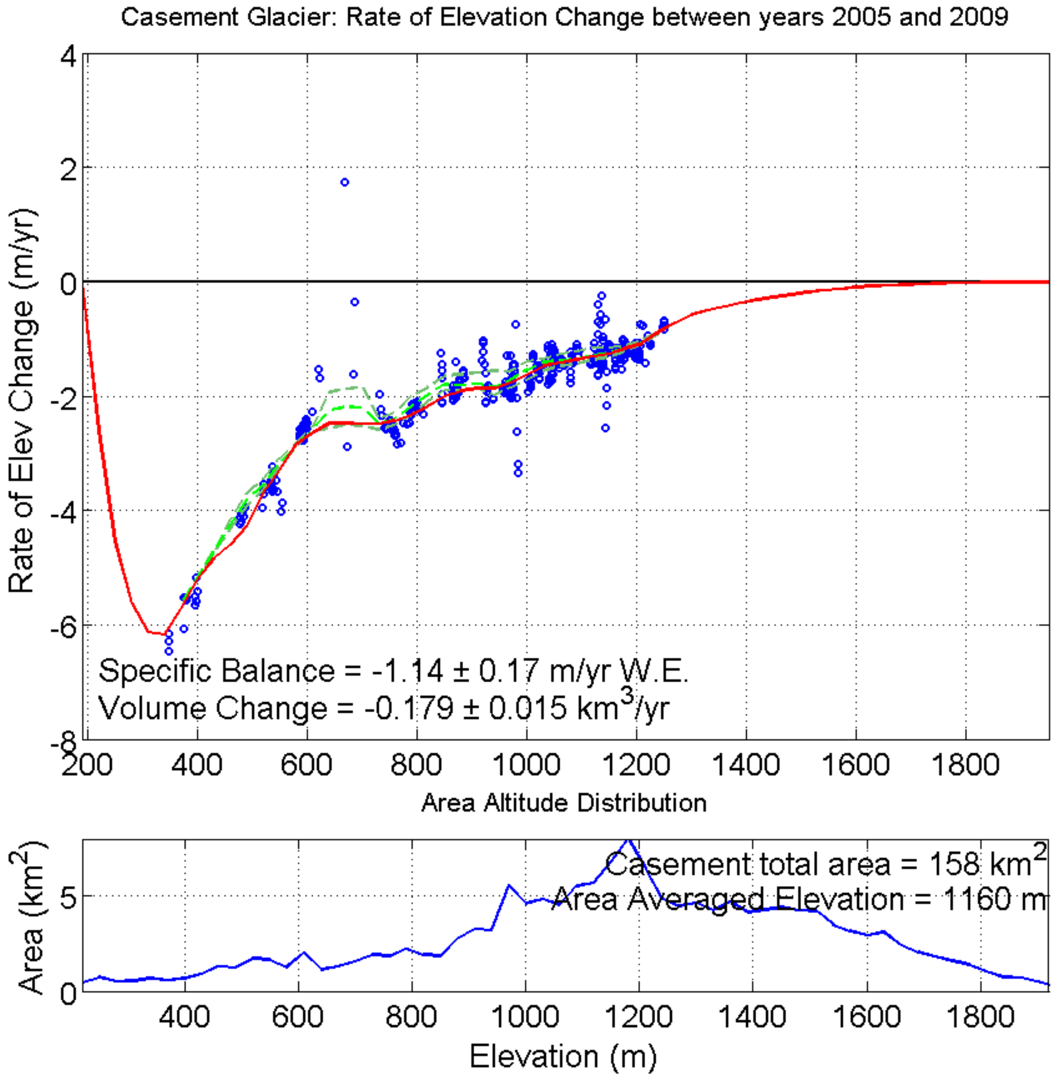
Brady Glacier: Rate of Elevation Change between years 2005 and 2009
Rate of Elev Change (m/yr)
Specific Balance = -0.69 ± 0.07 m/yr W.E.
Volume Change = -0.345 ± 0.032 km3/yr
Area Altitude Distribution
Area (km2)
Brady total area = 498 km2
Area Averaged Elevation = 720 m
Elevation (m)

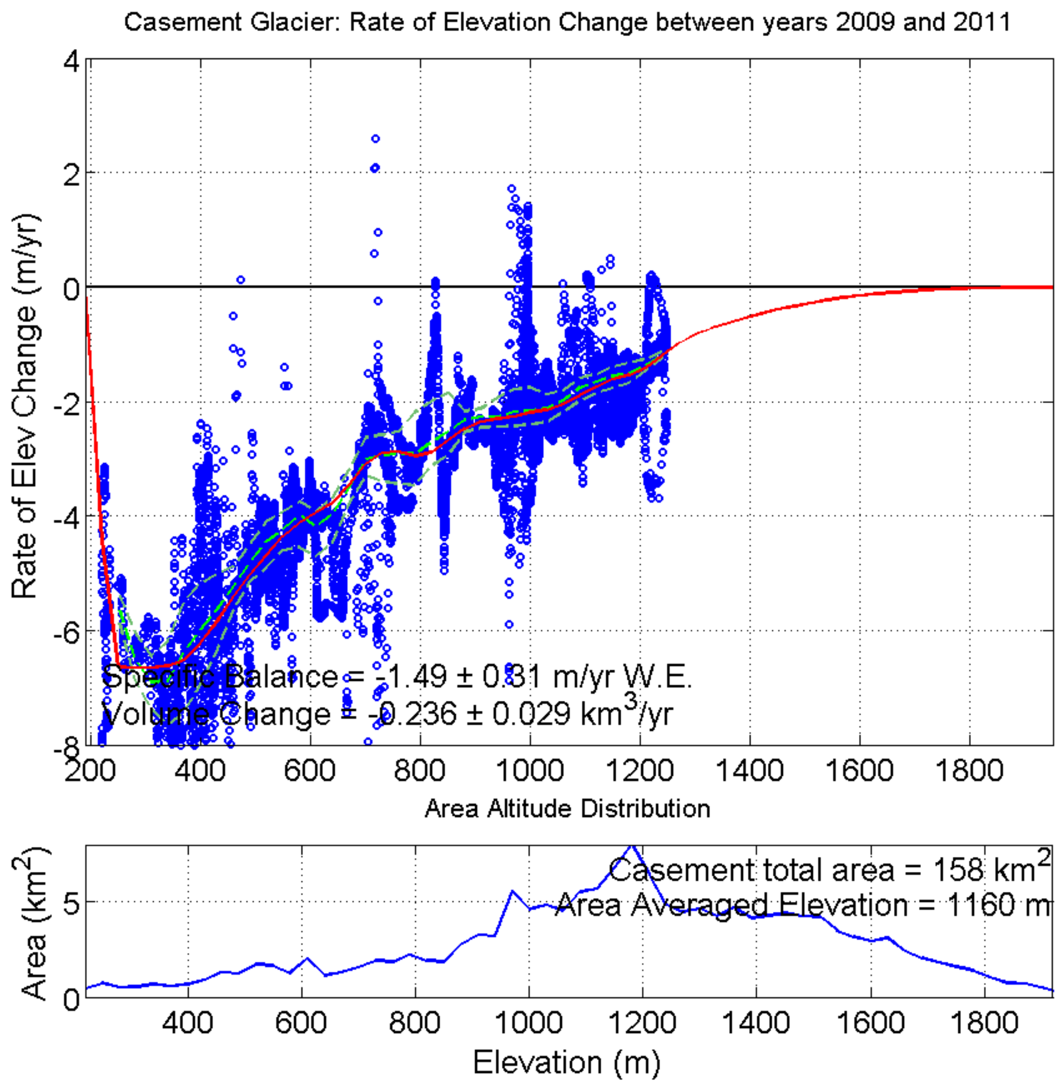


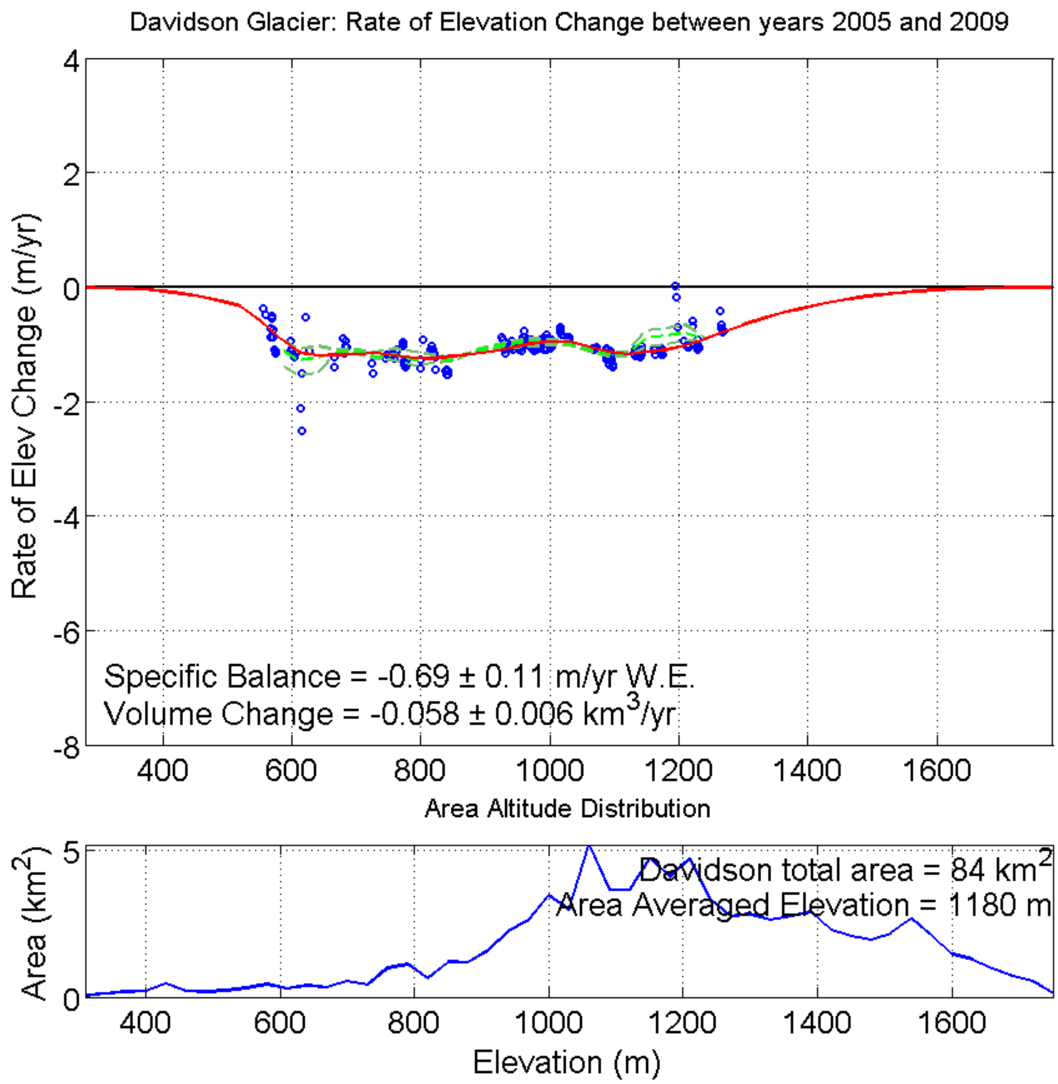
Brady Glacier: Rate of Elevation Change between years 2009 and 2011
Rate of Elev Change (m/yr)
Specific Balance = -1.32 ± 0.18 m/yr W.E.
Volume Change = -0.659 ± 0.084 km3/yr
Area Altitude Distribution
Area (km2)
Brady total area = 498 km2
Area Averaged Elevation = 720 m
Elevation (m)



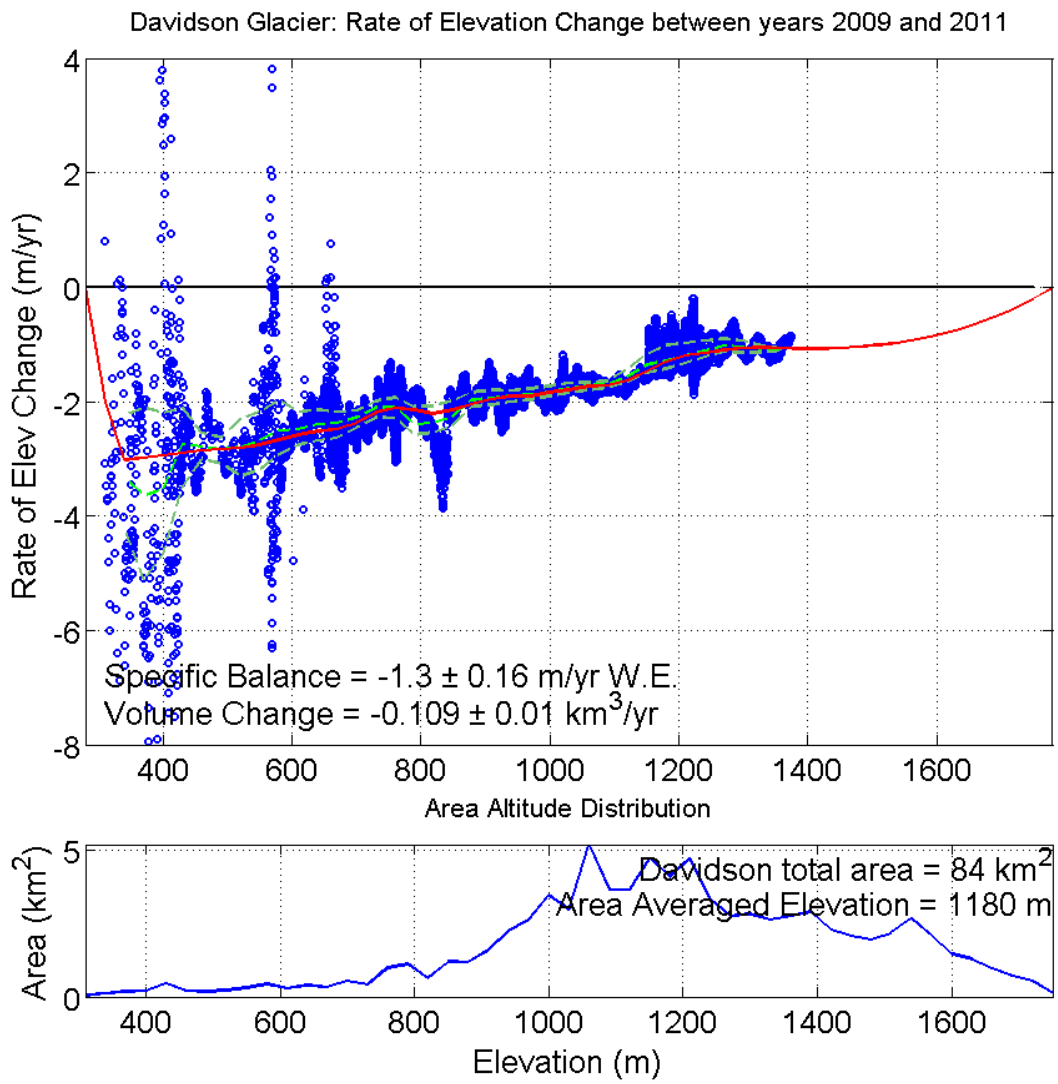
Carroll Glacier: Rate of Elevation Change between years 2009 and 2011
Rate of Elev Change (m/yr)
4
2
0
-2
-4
-6
-8
Specific Balance = -0.46 ± 0.44 m/yr W.E.
Volume Change = -0.182 ± 0.174 km^3/yr
200
400
600
800
1000
1200
1400
1600
1800
Area Altitude Distribution
Area (km^2)
10
5
0
Carroll total area = 397 km^2
Area Averaged Elevation = 1030 m
Elevation (m)

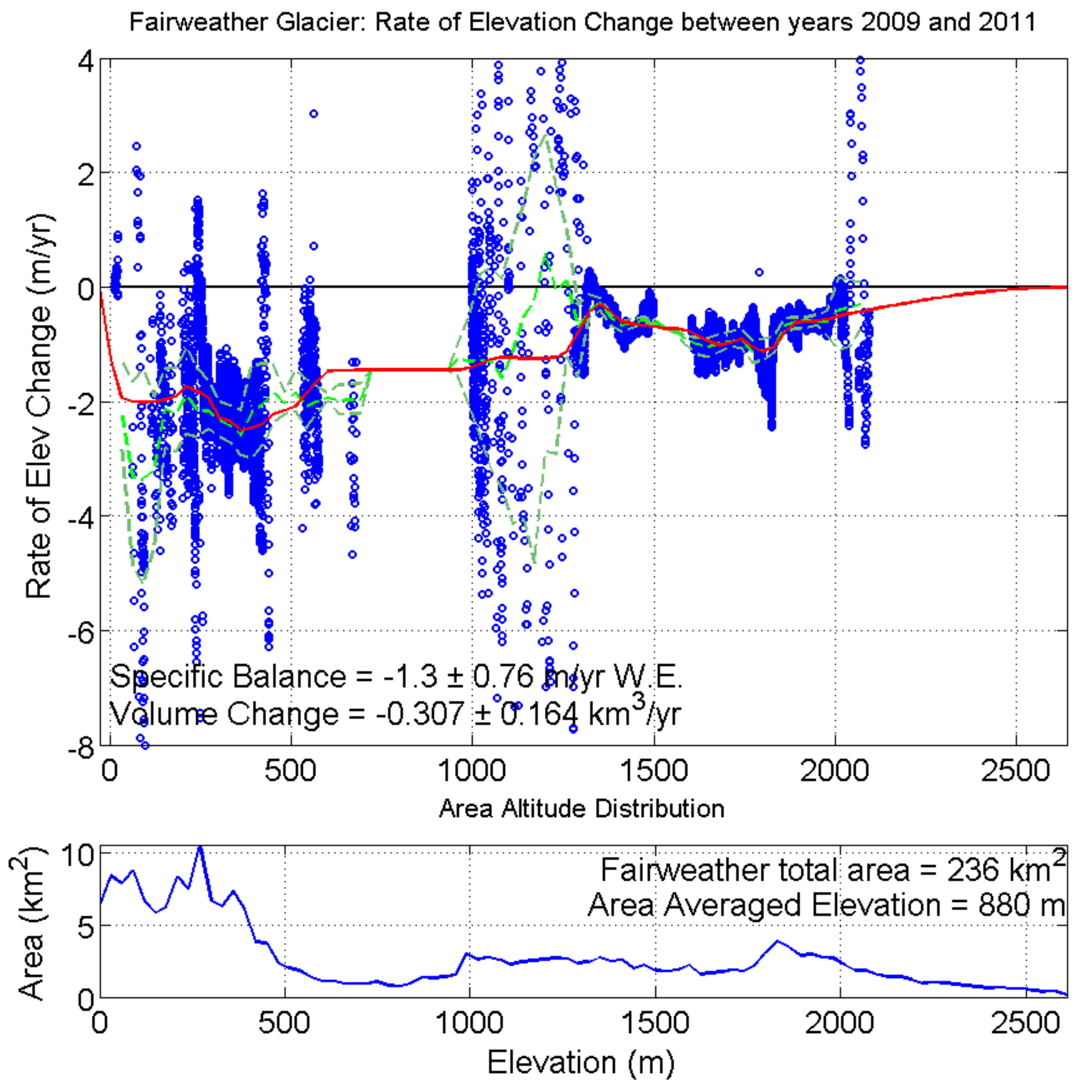

Casement Glacier: Rate of Elevation Change between years 2005 and 2009
Rate of Elev Change (m/yr)
Specific Balance = -1.14 ± 0.17 m/yr W.E.
Volume Change = -0.179 ± 0.015 km3/yr
4
2
0
-2
-4
-6
-8
200
400
600
800
1000
1200
1400
1600
1800
Area Altitude Distribution
Area (km2)
Casement total area = 158 km2
Area Averaged Elevation = 1160 m
Elevation (m)


Casement Glacier: Rate of Elevation Change between years 2009 and 2011
Rate of Elev Change (m/yr)
Specific Balance = -1.49 ± 0.31 m/yr W.E.
Volume Change = -0.236 ± 0.029 km3/yr
Area Altitude Distribution
Area (km2)
Casement total area = 158 km2
Area Averaged Elevation = 1160 m
Elevation (m)

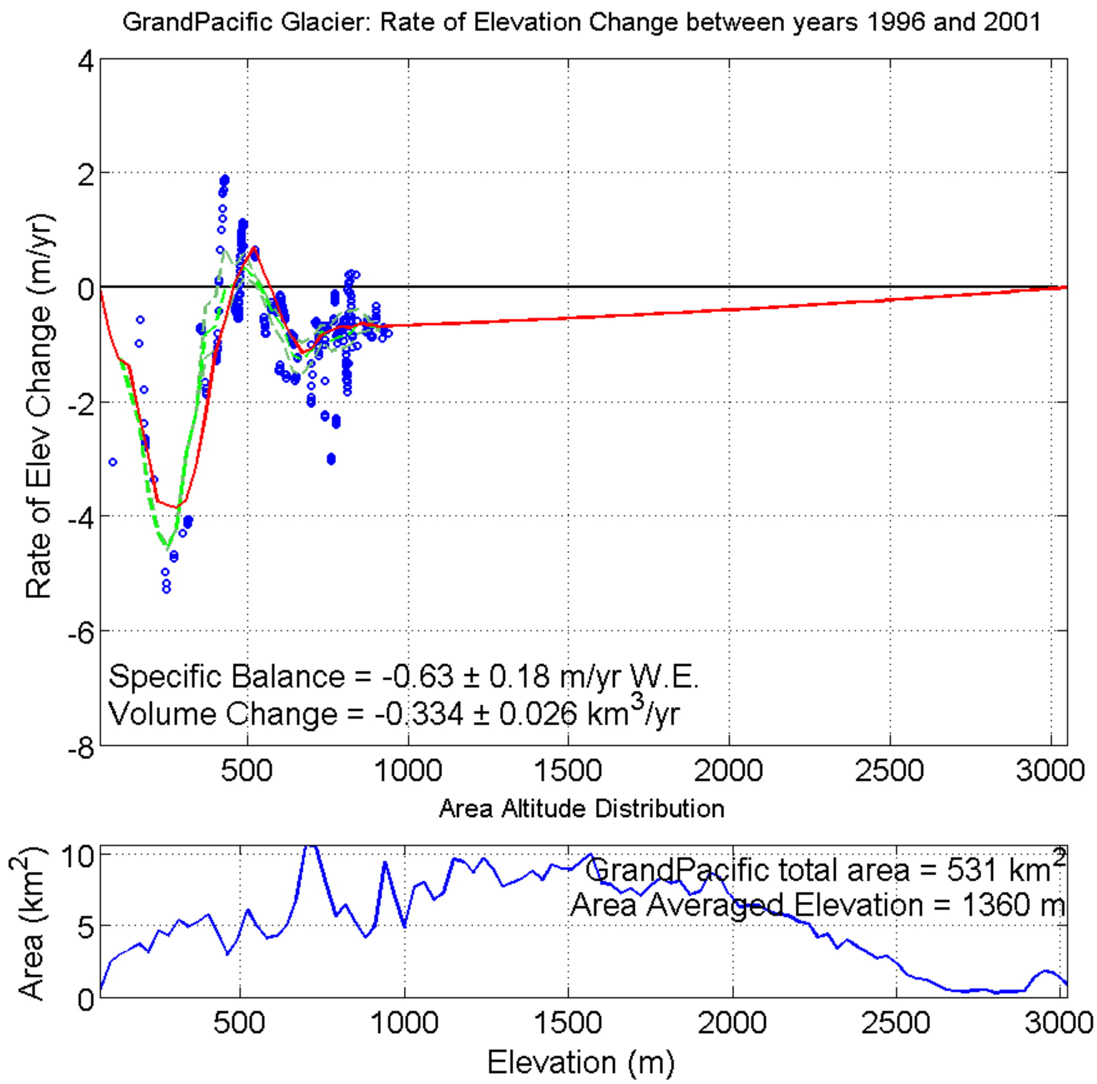


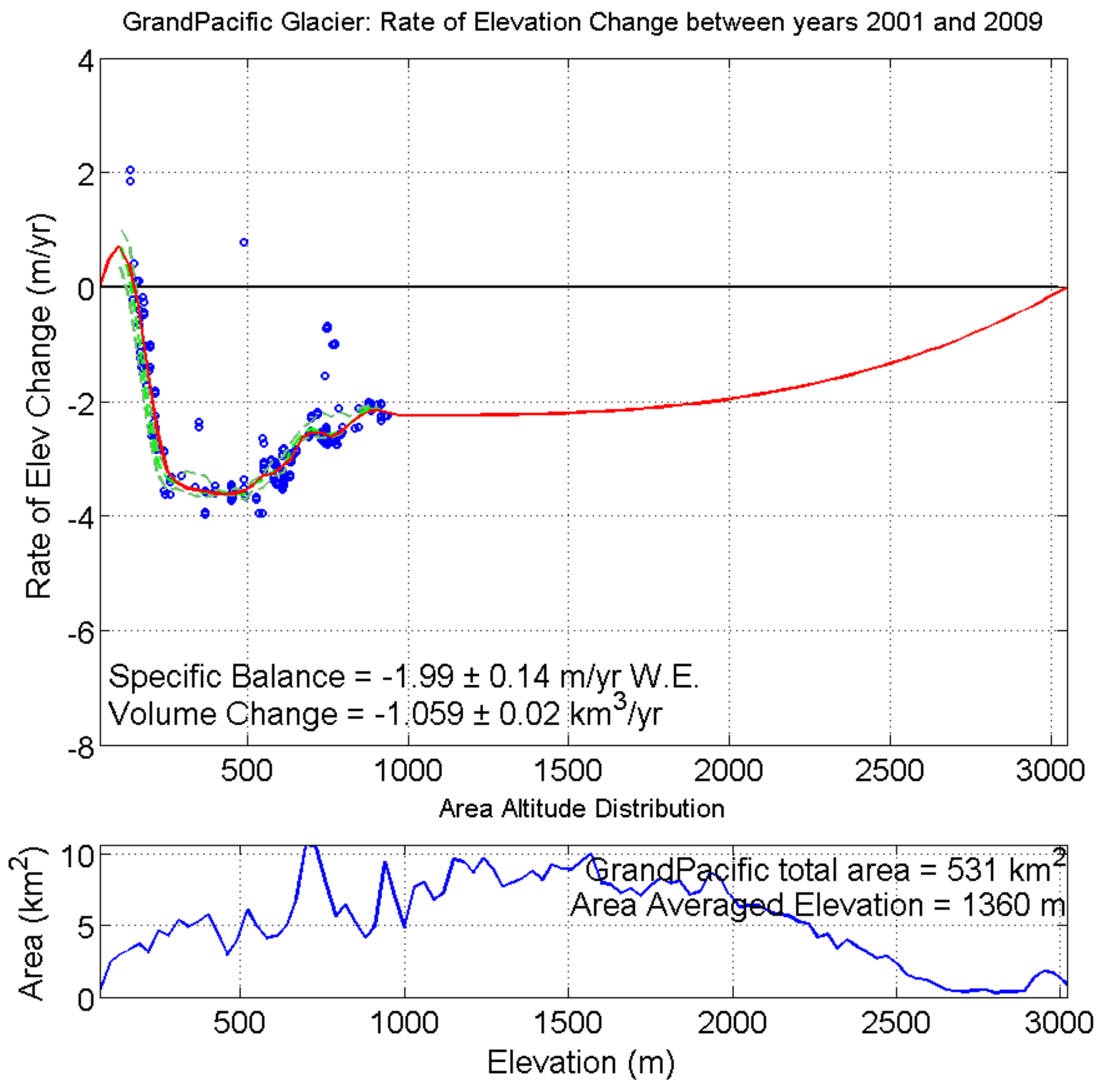
Davidson Glacier: Rate of Elevation Change between years 2005 and 2009
Rate of Elev Change (m/yr)
Specific Balance = -0.69 ± 0.11 m/yr W.E.
Volume Change = -0.058 ± 0.006 km3/yr
Area Altitude Distribution
Area (km2)
Davidson total area = 84 km2
Area Averaged Elevation = 1180 m
Elevation (m)

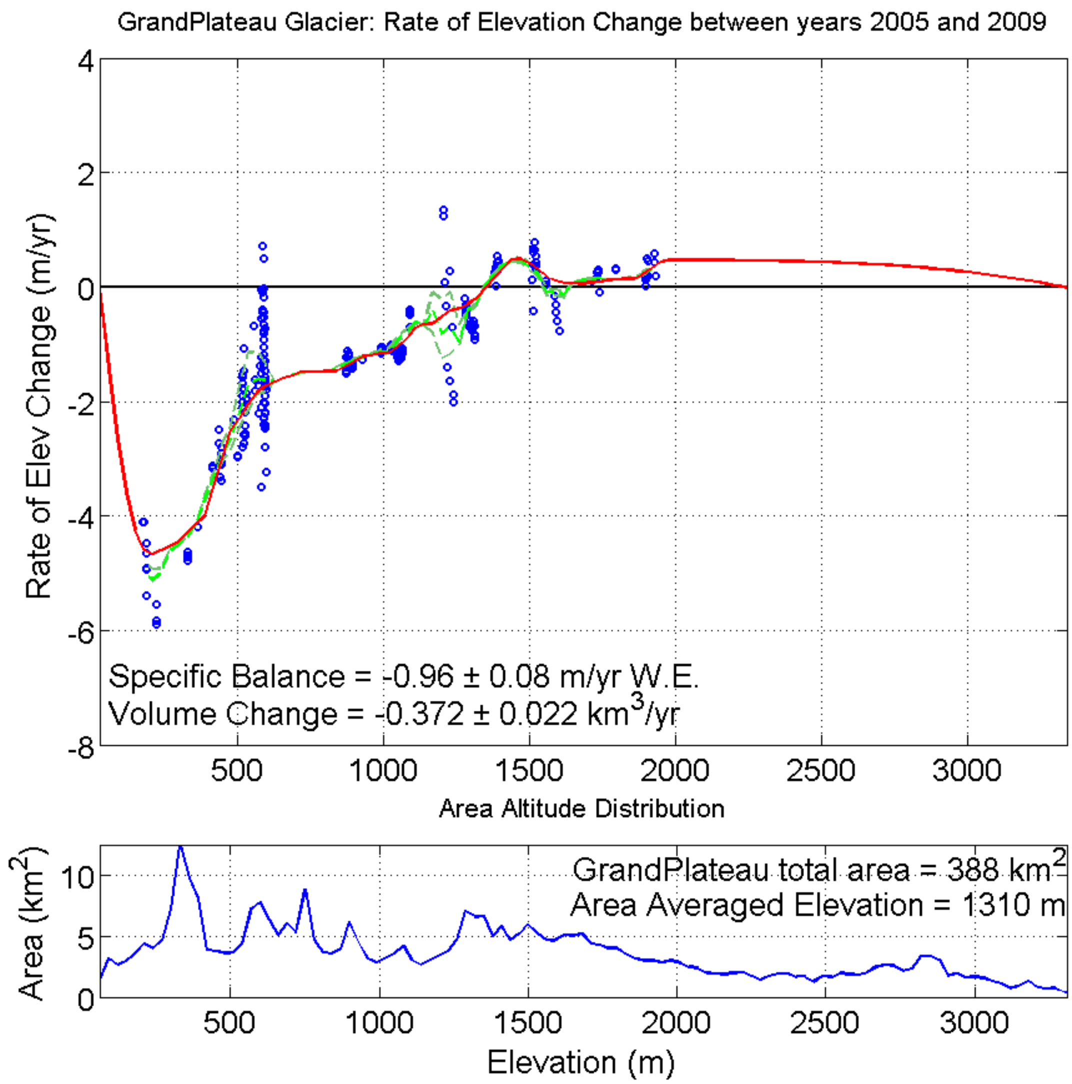

Davidson Glacier: Rate of Elevation Change between years 2009 and 2011
Rate of Elev Change (m/yr)
Specific Balance = -1.3 ± 0.16 m/yr W.E.
Volume Change = -0.109 ± 0.01 km^3/yr
Area Altitude Distribution
Area (km^2)
Davidson total area = 84 km^2
Area Averaged Elevation = 1180 m
Elevation (m)



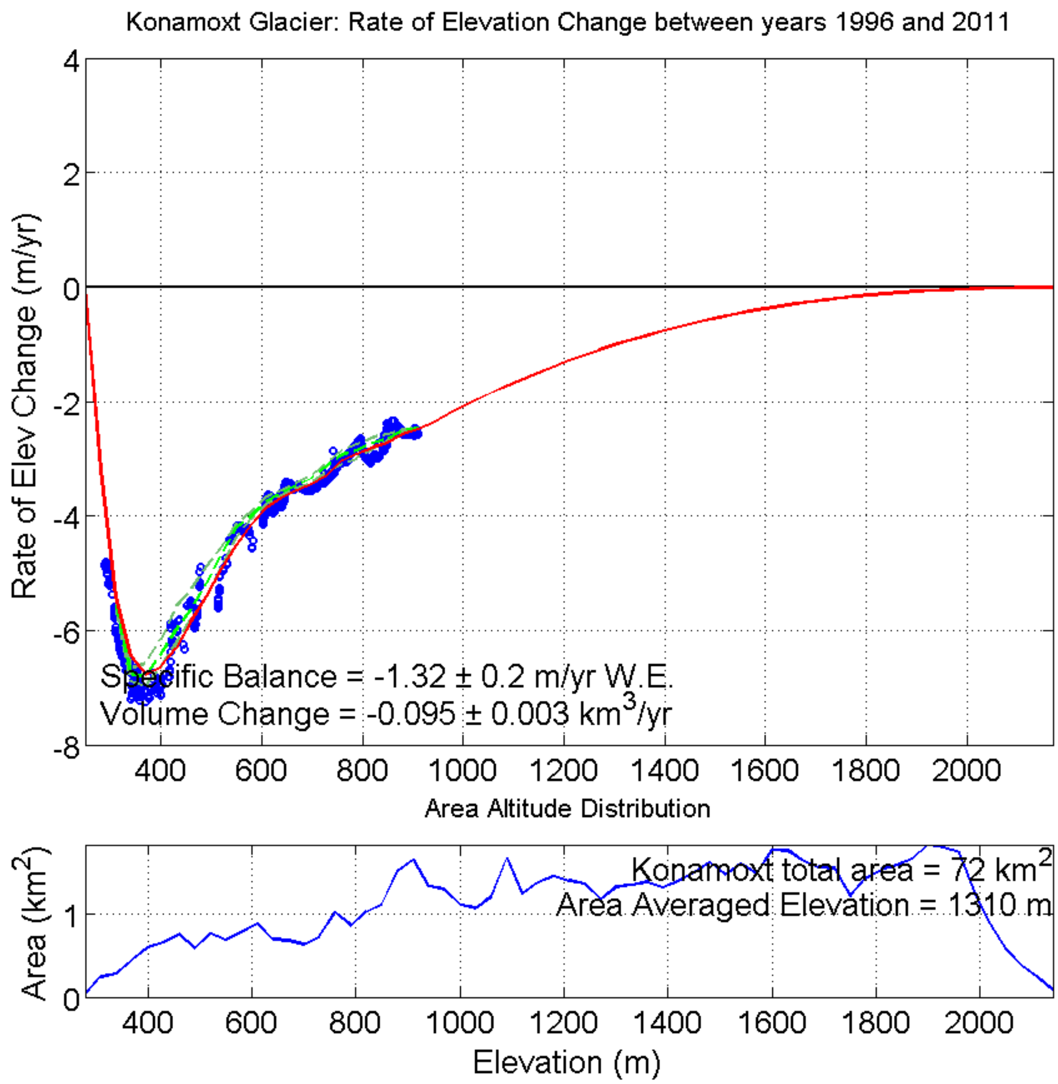
Fairweather Glacier: Rate of Elevation Change between years 2009 and 2011
Rate of Elev Change (m/yr)
4
2
0
-2
-4
-6
-8
0
500
1000
1500
2000
2500
Specific Balance = -1.3 ± 0.76 m/yr W.E.
Volume Change = -0.307 ± 0.164 km3/yr
Area Altitude Distribution
Area (km2)
10
5
0
Fairweather total area = 236 km2
Area Averaged Elevation = 880 m
Elevation (m)

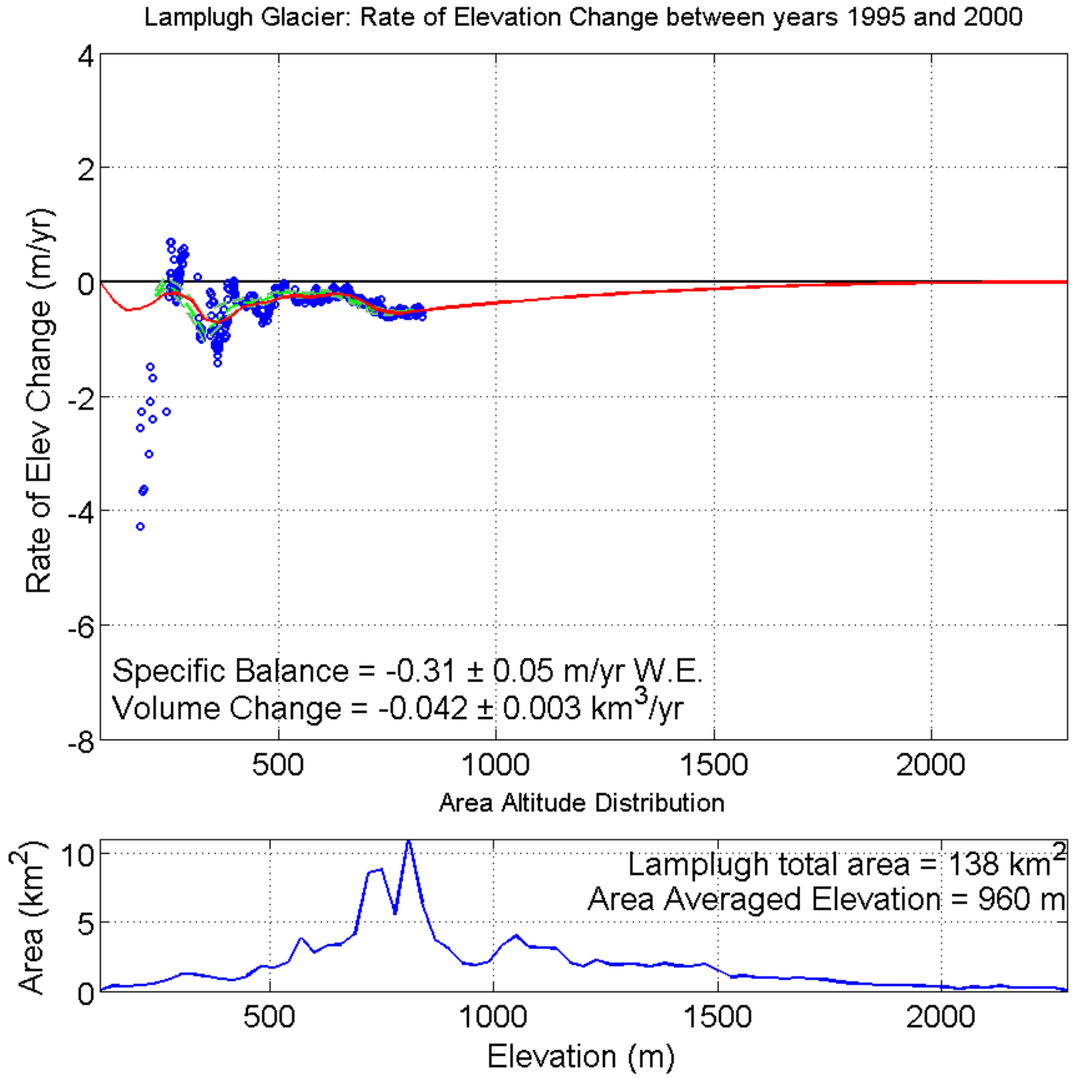

GrandPacific Glacier: Rate of Elevation Change between years 1996 and 2001
Rate of Elev Change (m/yr)
Specific Balance = -0.63 ± 0.18 m/yr W.E.
Volume Change = -0.334 ± 0.026 km3/yr
Area Altitude Distribution
Area (km2)
GrandPacific total area = 531 km2
Area Averaged Elevation = 1360 m
Elevation (m)


GrandPacific Glacier: Rate of Elevation Change between years 2001 and 2009
Rate of Elev Change (m/yr)
Specific Balance = -1.99 ± 0.14 m/yr W.E.
Volume Change = -1.059 ± 0.02 km3/yr
Area Altitude Distribution
Area (km2)
GrandPacific total area = 531 km2
Area Averaged Elevation = 1360 m
Elevation (m)

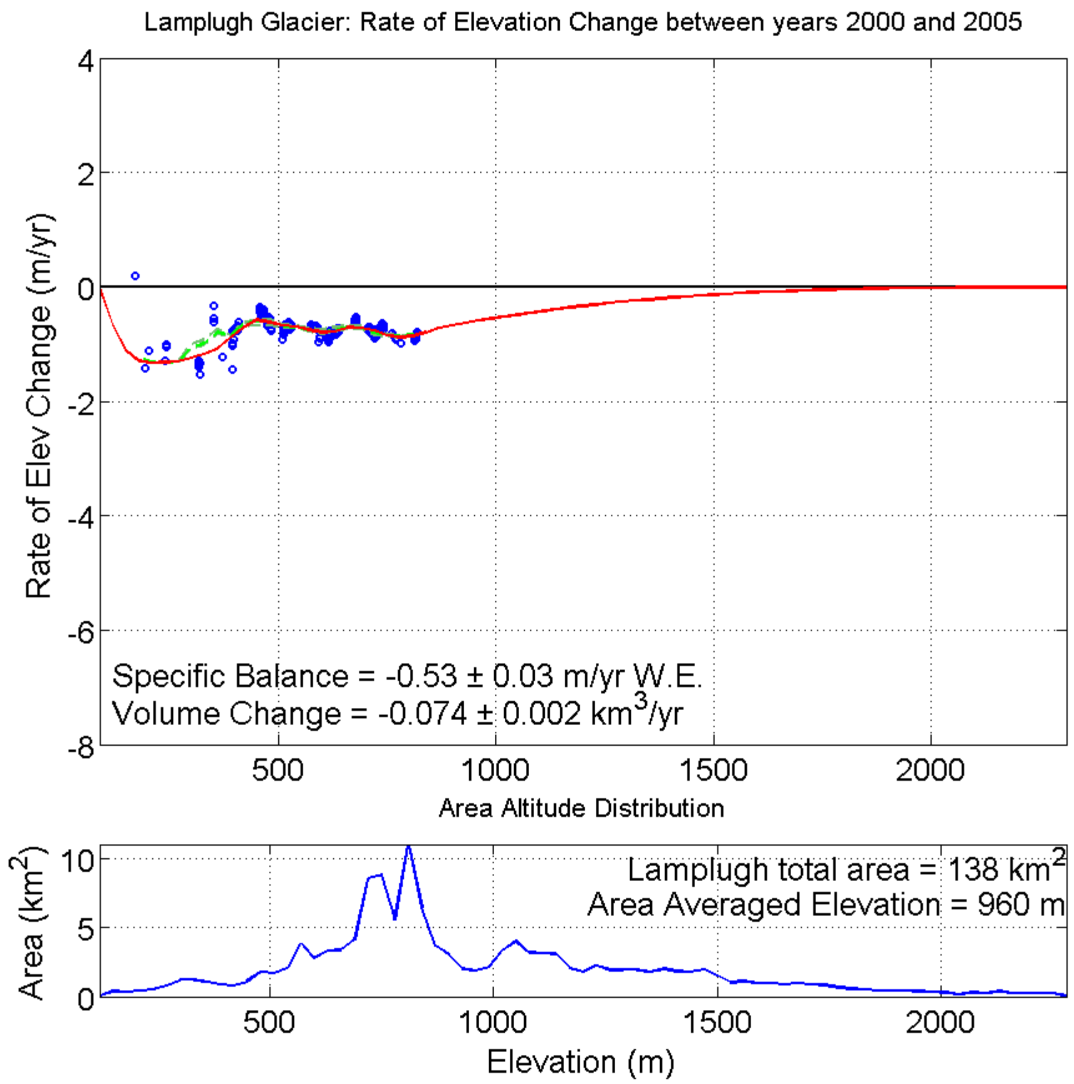


GrandPlateau Glacier: Rate of Elevation Change between years 2005 and 2009
Rate of Elev Change (m/yr)
4
2
0
-2
-4
-6
-8
500
1000
1500
2000
2500
3000
Specific Balance = -0.96 ± 0.08 m/yr W.E.
Volume Change = -0.372 ± 0.022 km3/yr
Area Altitude Distribution
Area (km2)
10
5
0
GrandPlateau total area = 388 km2
Area Averaged Elevation = 1310 m
Elevation (m)

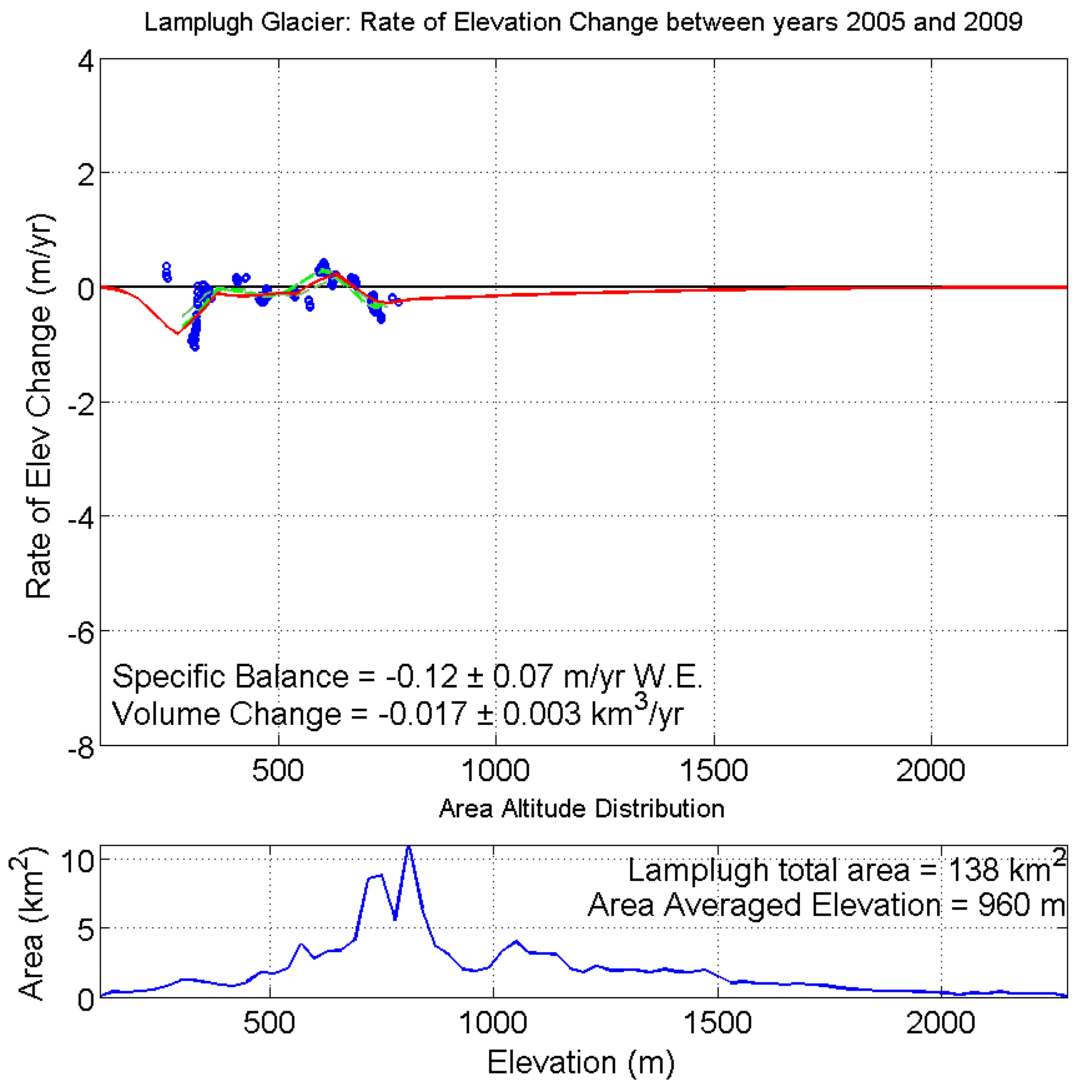

Konamoxt Glacier: Rate of Elevation Change between years 1996 and 2011
Rate of Elev Change (m/yr)
Specific Balance = -1.32 ± 0.2 m/yr W.E.
Volume Change = -0.095 ± 0.003 km3/yr
Area Altitude Distribution
Area (km2)
Konamoxt total area = 72 km2
Area Averaged Elevation = 1310 m
Elevation (m)
4
2
0
-2
-4
-6
-8
1
400
600
800
1000
1200
1400
1600
1800
2000

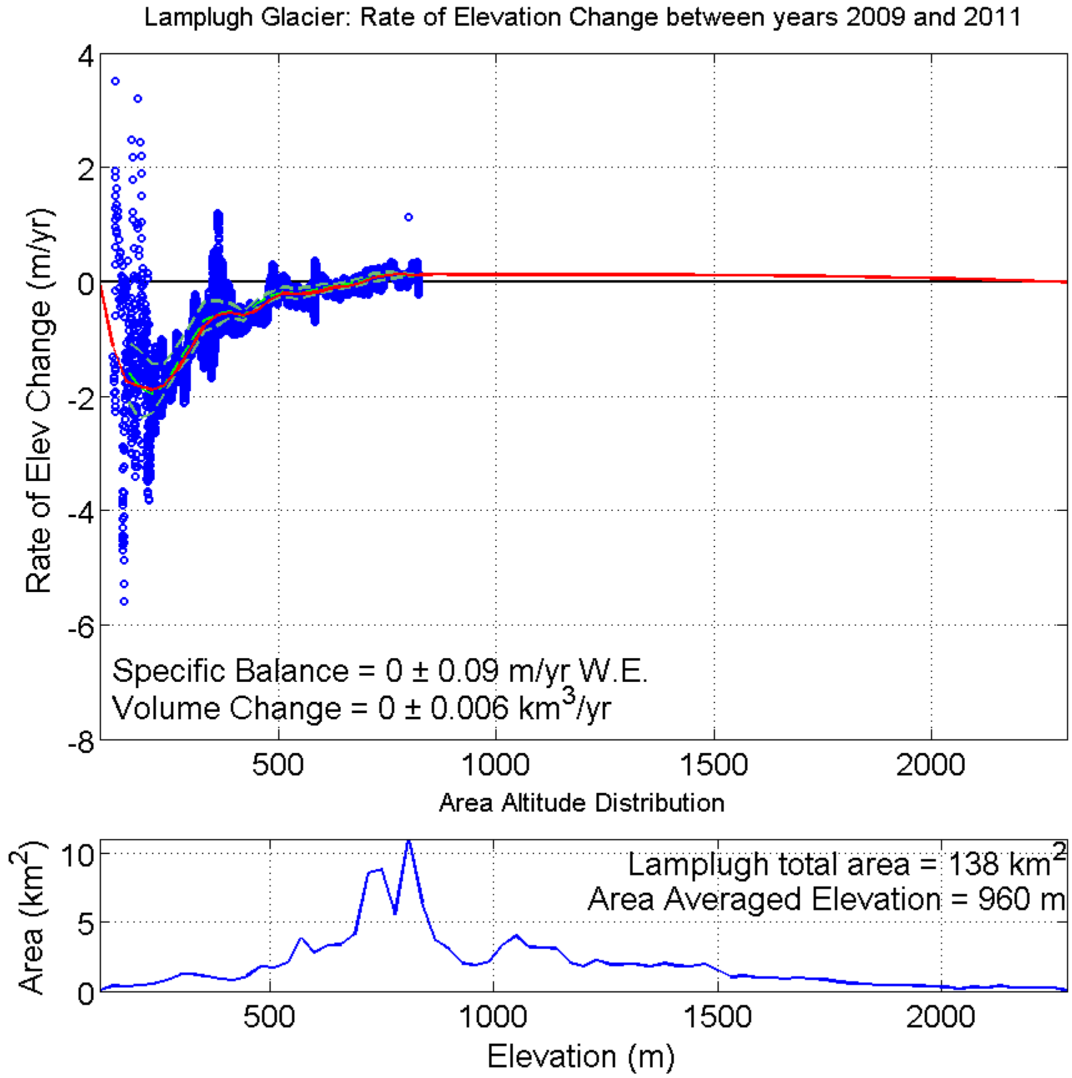


Lamplugh Glacier: Rate of Elevation Change between years 1995 and 2000
Rate of Elev Change (m/yr)
Specific Balance = -0.31 ± 0.05 m/yr W.E.
Volume Change = -0.042 ± 0.003 km3/yr
Area Altitude Distribution
Area (km2)
Lamplugh total area = 138 km2
Area Averaged Elevation = 960 m
Elevation (m)

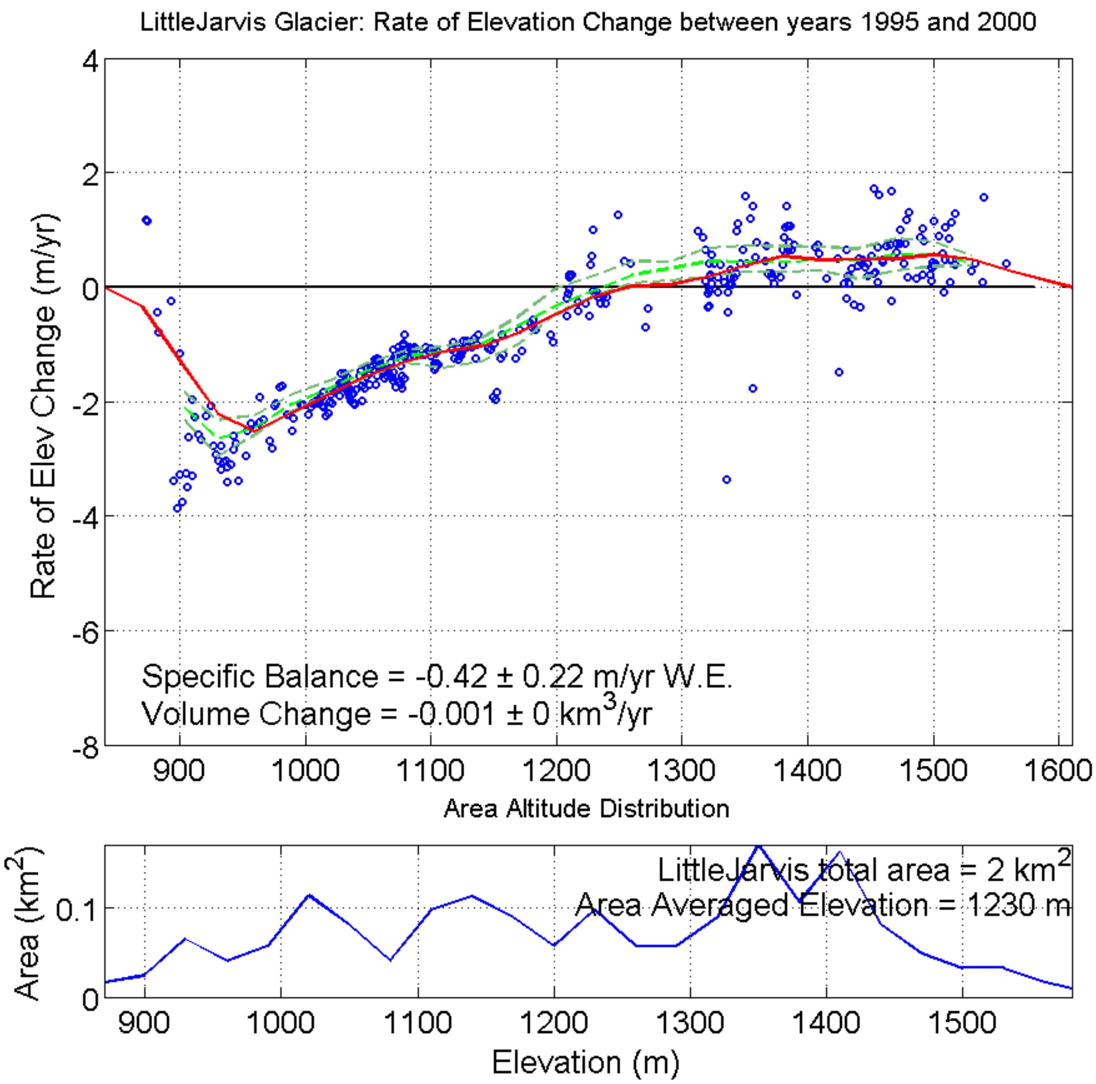


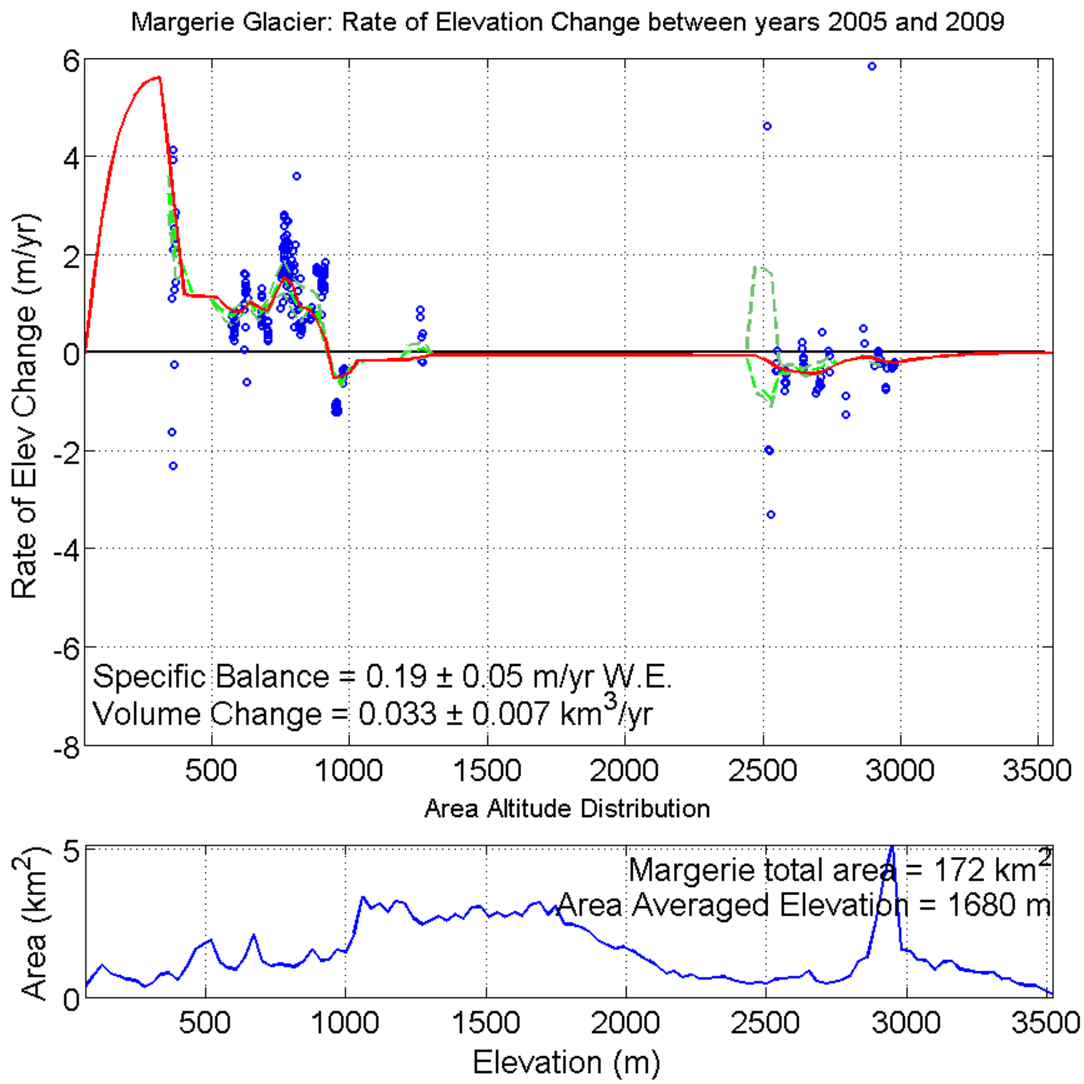
Lamplugh Glacier: Rate of Elevation Change between years 2000 and 2005
Rate of Elev Change (m/yr)
Specific Balance = -0.53 ± 0.03 m/yr W.E.
Volume Change = -0.074 ± 0.002 km^3/yr
Area Altitude Distribution
Area (km^2)
Lamplugh total area = 138 km^2
Area Averaged Elevation = 960 m
Elevation (m)


Lamplugh Glacier: Rate of Elevation Change between years 2005 and 2009
Rate of Elev Change (m/yr)
4
2
0
-2
-4
-6
-8
500
1000
1500
2000
Specific Balance = -0.12 ± 0.07 m/yr W.E.
Volume Change = -0.017 ± 0.003 km^3/yr
Area Altitude Distribution
Area (km^2)
10
5
0
Lamplugh total area = 138 km^2
Area Averaged Elevation = 960 m
500
1000
1500
2000
Elevation (m)

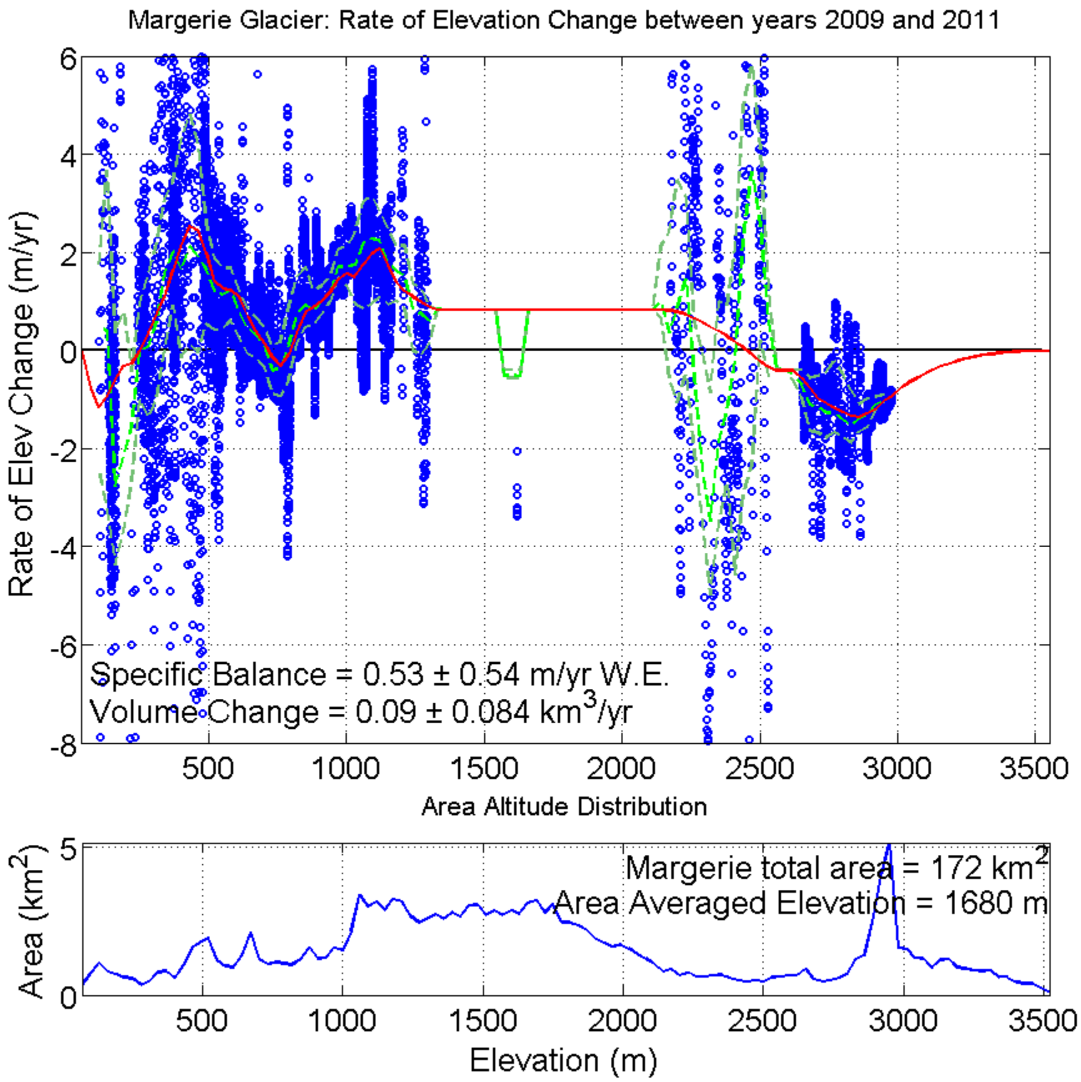


Lamplugh Glacier: Rate of Elevation Change between years 2009 and 2011
Rate of Elev Change (m/yr)
Specific Balance = 0 ± 0.09 m/yr W.E.
Volume Change = 0 ± 0.006 km^3/yr
Area Altitude Distribution
Area (km^2)
Lamplugh total area = 138 km^2
Area Averaged Elevation = 960 m
Elevation (m)

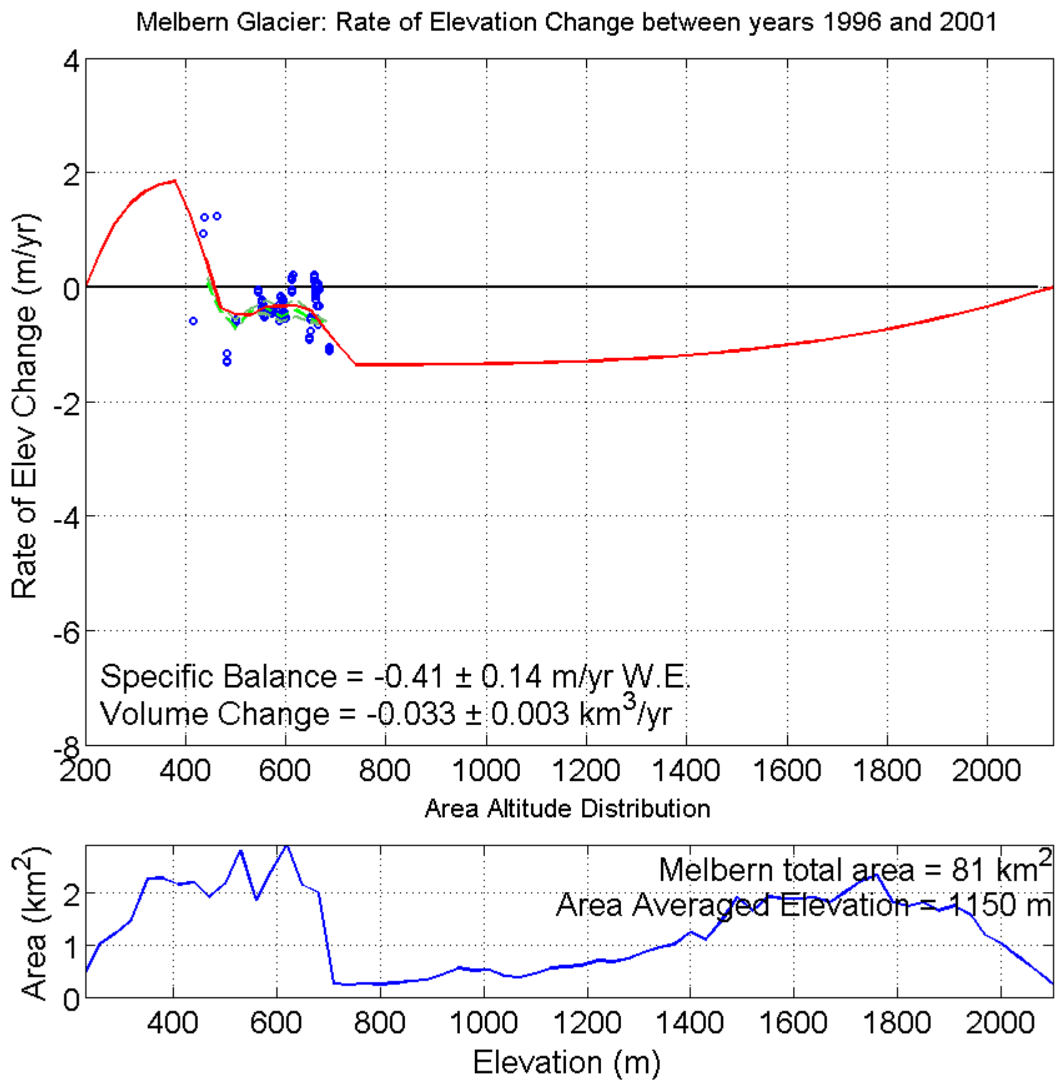

LittleJarvis Glacier: Rate of Elevation Change between years 1995 and 2000
Rate of Elev Change (m/yr)
4
2
0
-2
-4
-6
-8
900
1000
1100
1200
1300
1400
1500
1600
Specific Balance = -0.42 ± 0.22 m/yr W.E.
Volume Change = -0.001 ± 0 km3/yr
Area Altitude Distribution
Area (km2)
0.1
0
LittleJarvis total area = 2 km2
Area Averaged Elevation = 1230 m
Elevation (m)

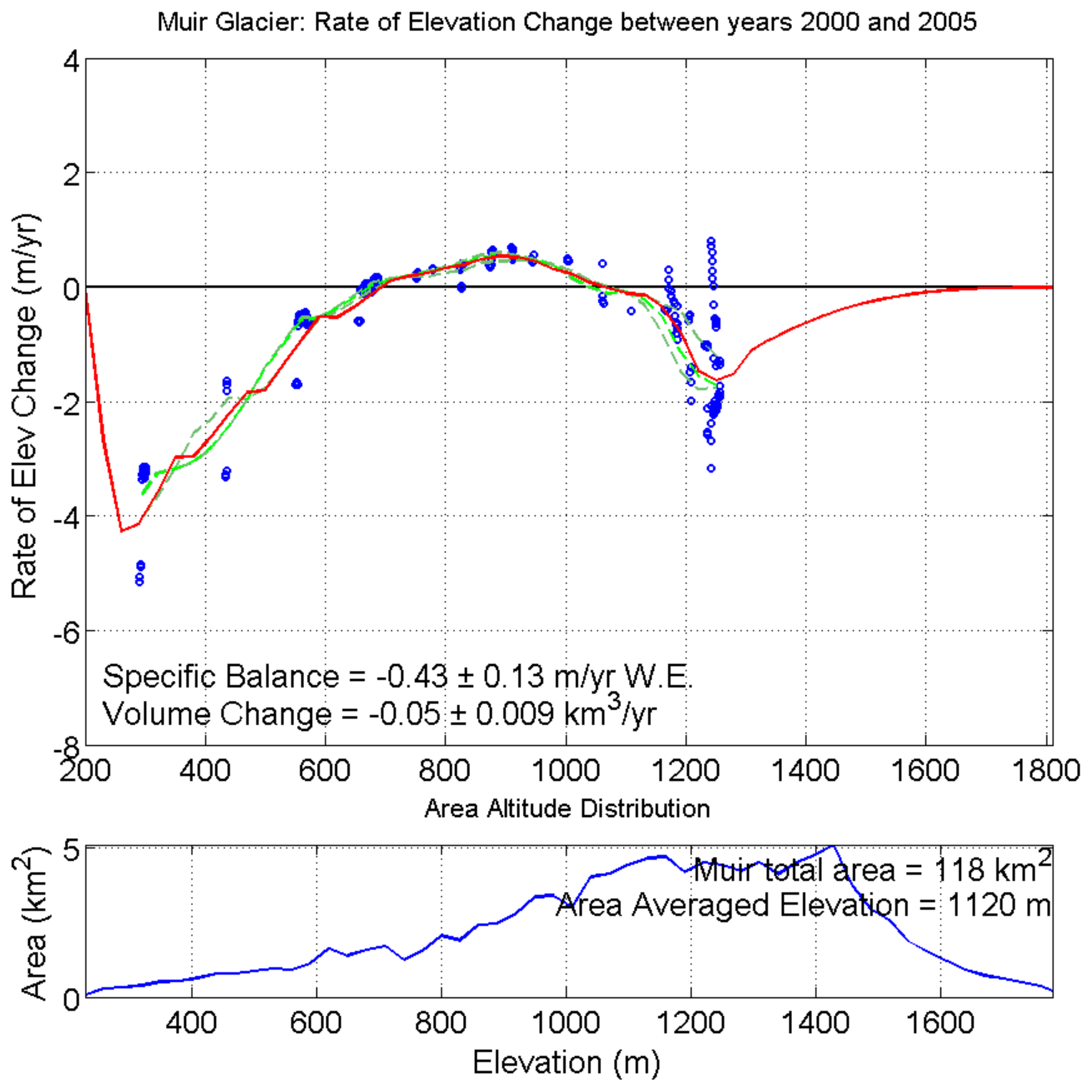


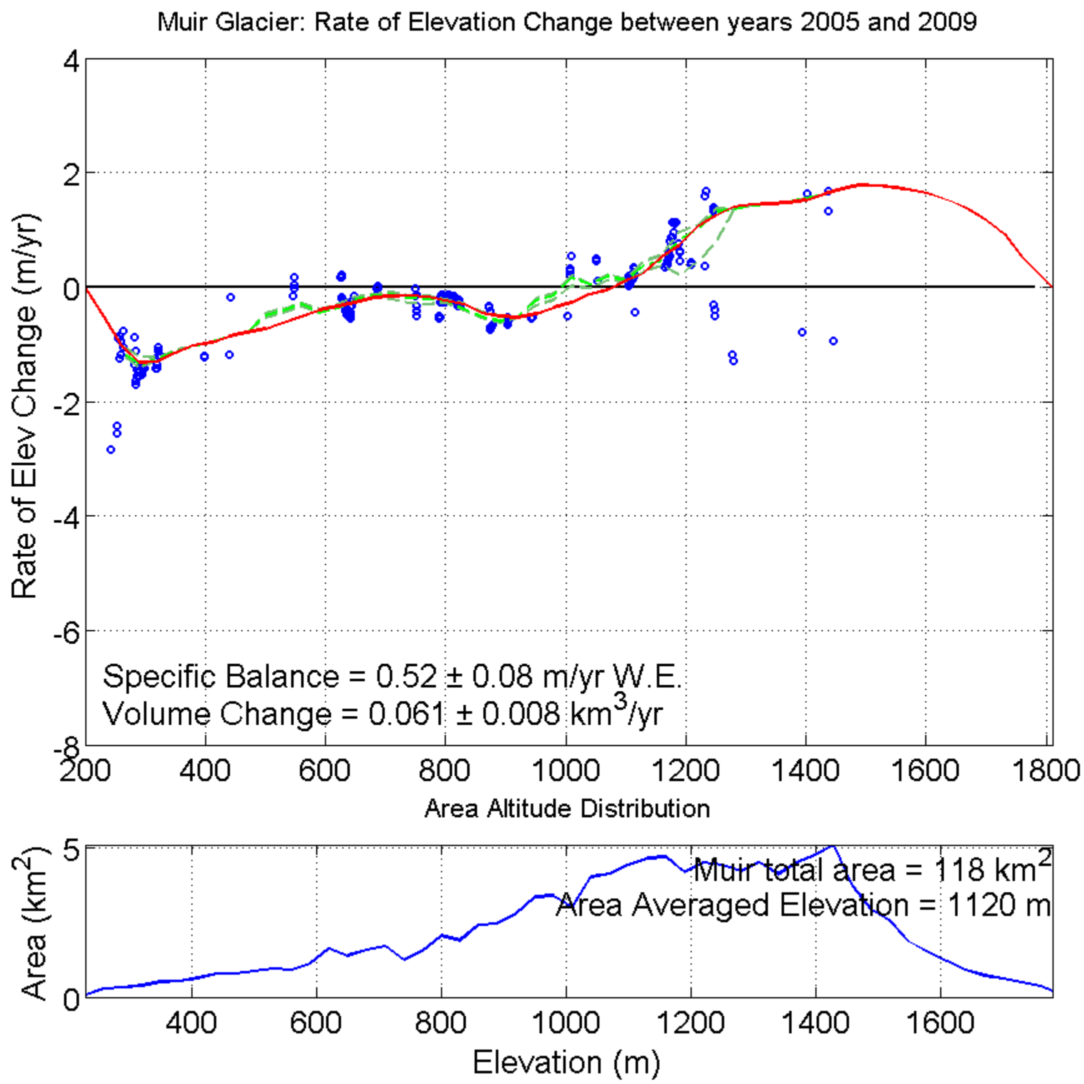
Margerie Glacier: Rate of Elevation Change between years 2005 and 2009
Rate of Elev Change (m/yr)
6
4
2
0
-2
-4
-6
-8
Specific Balance = 0.19 ± 0.05 m/yr W.E.
Volume Change = 0.033 ± 0.007 km³/yr
500
1000
1500
2000
2500
3000
3500
Area Altitude Distribution
Area (km²)
5
0
Margerie total area = 172 km²
Area Averaged Elevation = 1680 m
500
1000
1500
2000
2500
3000
3500
Elevation (m)

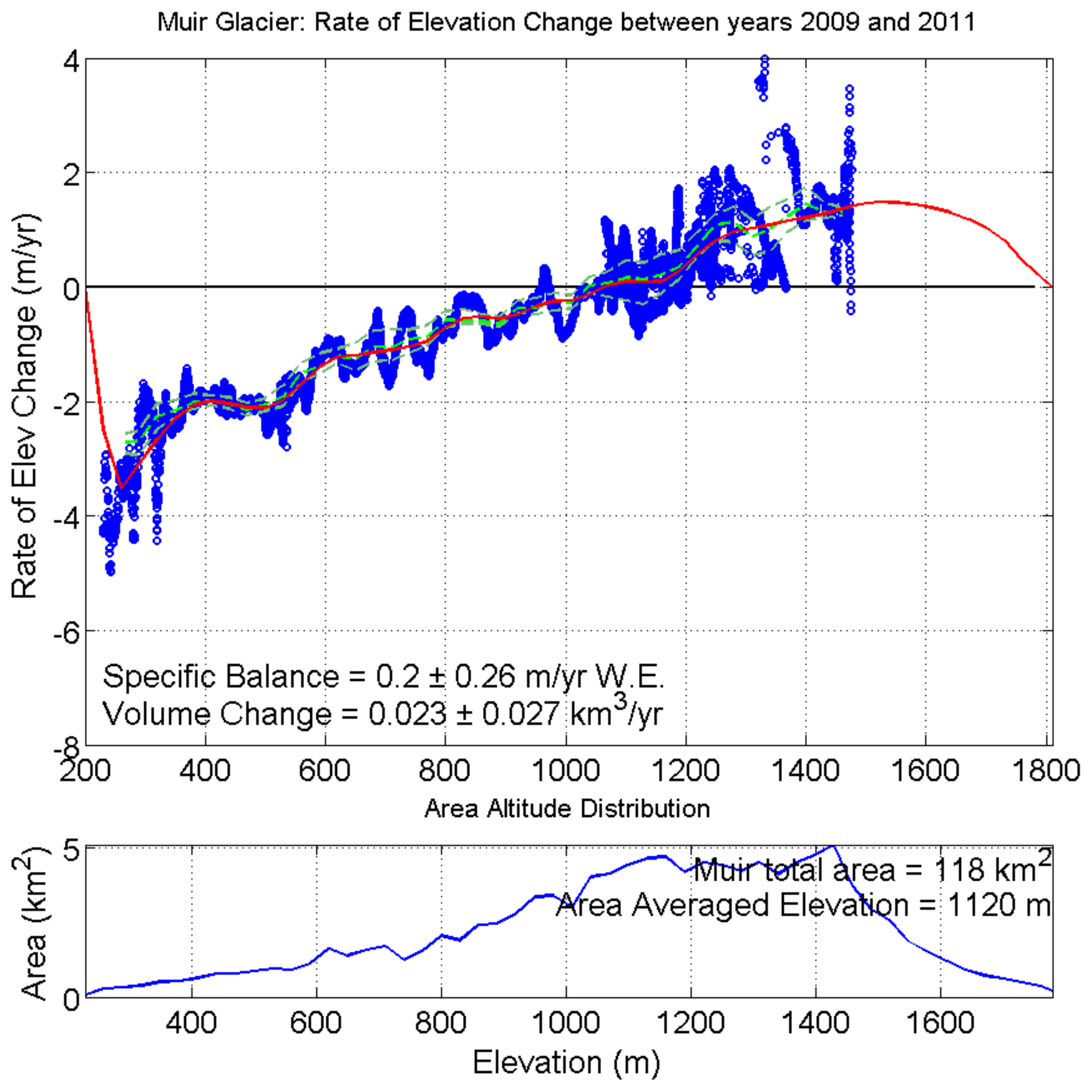


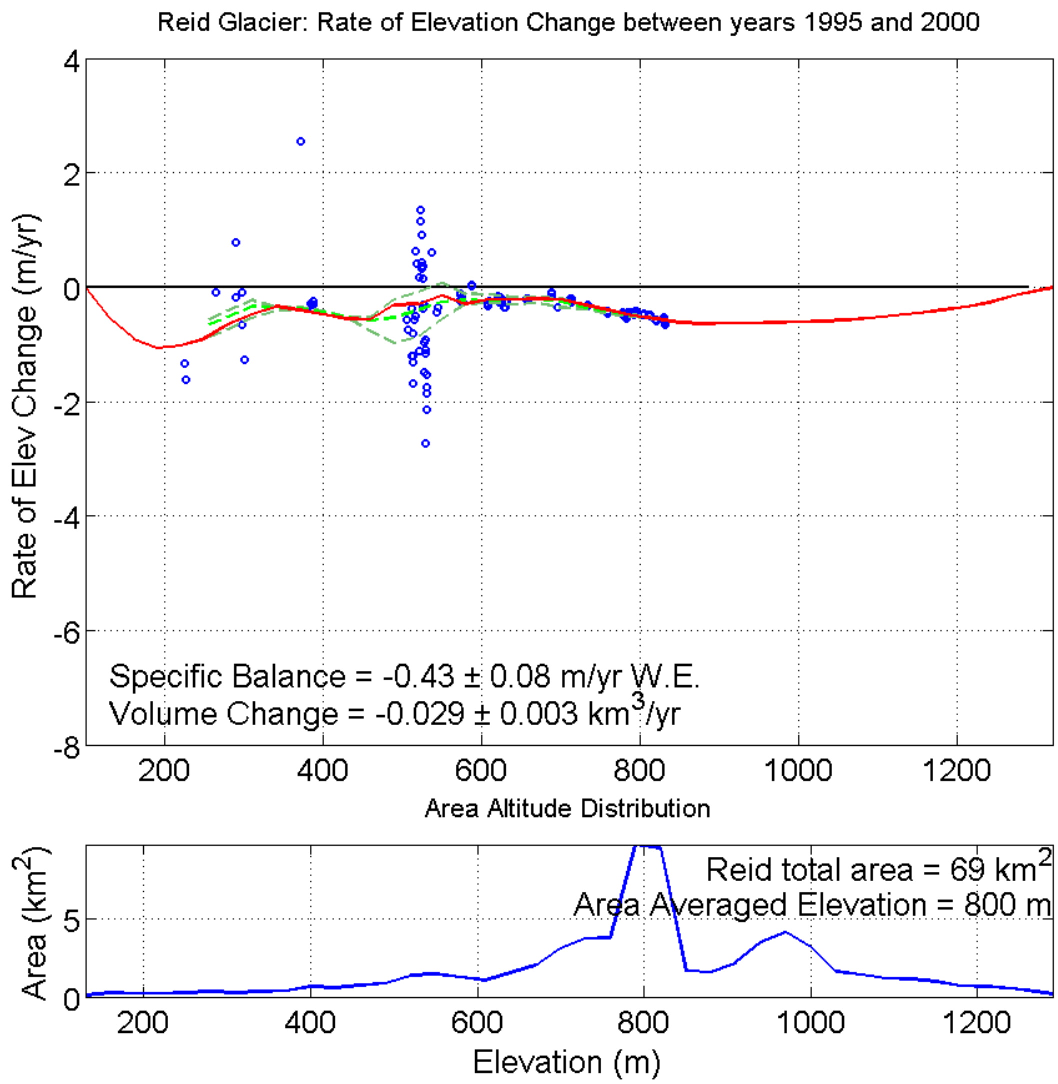
Margerie Glacier: Rate of Elevation Change between years 2009 and 2011
Rate of Elev Change (m/yr)
Specific Balance = 0.53 ± 0.54 m/yr W.E.
Volume Change = 0.09 ± 0.084 km³/yr
Area Altitude Distribution
Area (km²)
Margerie total area = 172 km²
Area Averaged Elevation = 1680 m
Elevation (m)


Melbern Glacier: Rate of Elevation Change between years 1996 and 2001
Rate of Elev Change (m/yr)
Specific Balance = -0.41 ± 0.14 m/yr W.E.
Volume Change = -0.033 ± 0.003 km^3/yr
Area Altitude Distribution
Area (km^2)
Melbern total area = 81 km^2
Area Averaged Elevation = 1150 m
Elevation (m)

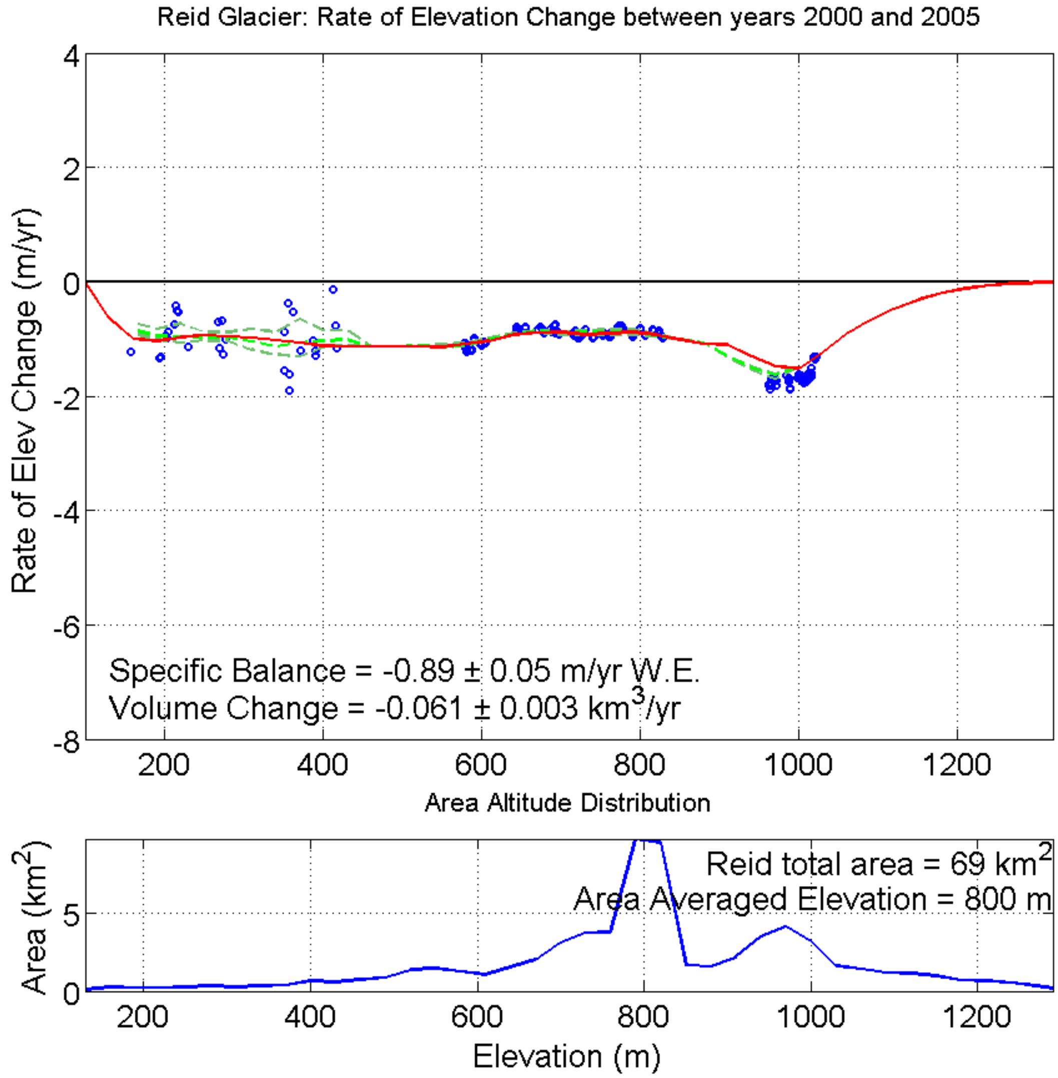

Muir Glacier: Rate of Elevation Change between years 2000 and 2005
Rate of Elev Change (m/yr)
Specific Balance = -0.43 ± 0.13 m/yr W.E.
Volume Change = -0.05 ± 0.009 km3/yr
Area Altitude Distribution
Area (km2)
Muir total area = 118 km2
Area Averaged Elevation = 1120 m
Elevation (m)


Muir Glacier: Rate of Elevation Change between years 2005 and 2009
Rate of Elev Change (m/yr)
4
2
0
-2
-4
-6
-8
Specific Balance = 0.52 ± 0.08 m/yr W.E.
Volume Change = 0.061 ± 0.008 km3/yr
200
400
600
800
1000
1200
1400
1600
1800
Area Altitude Distribution
Area (km2)
5
0
Muir total area = 118 km2
Area Averaged Elevation = 1120 m
400
600
800
1000
1200
1400
1600
Elevation (m)

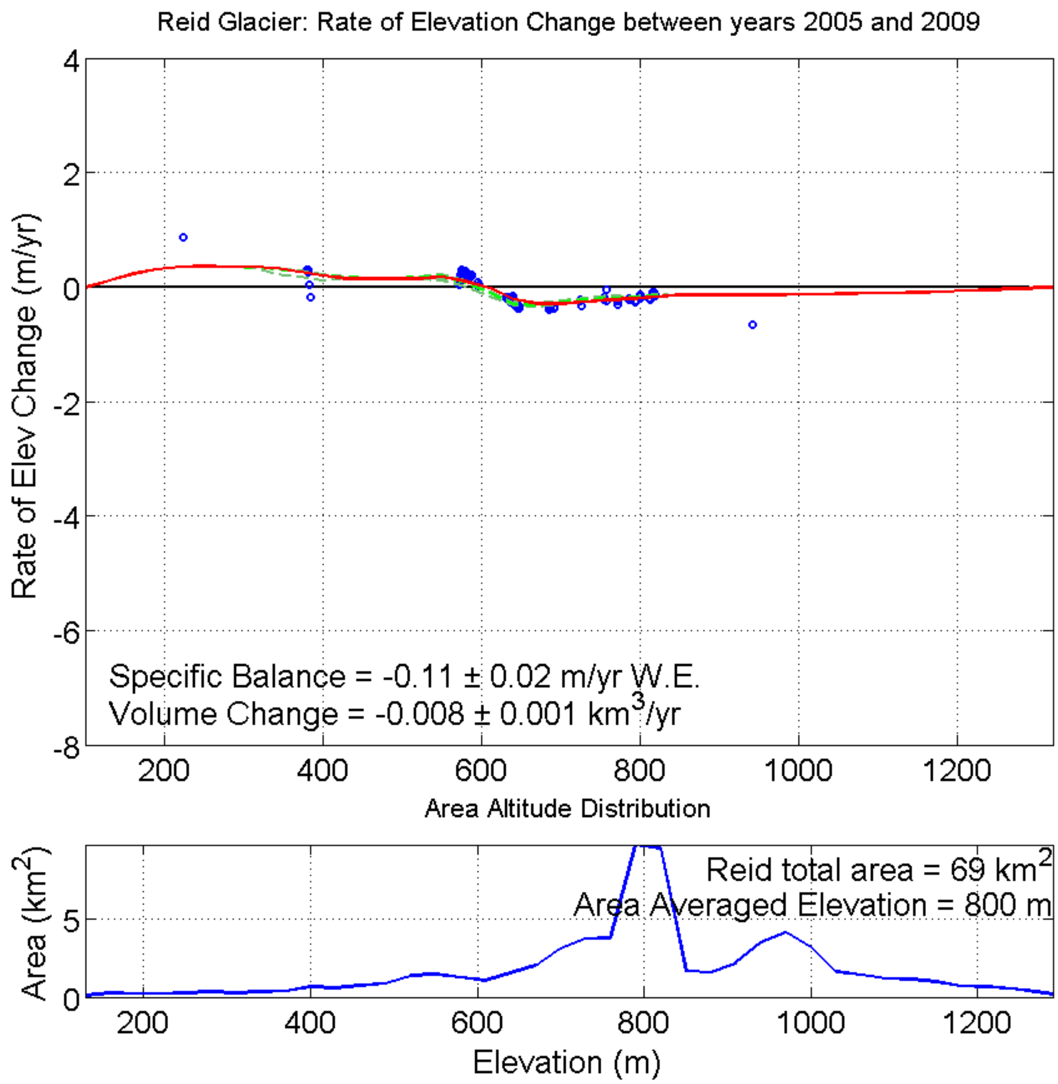

Muir Glacier: Rate of Elevation Change between years 2009 and 2011
Rate of Elev Change (m/yr)
Specific Balance = 0.2 ± 0.26 m/yr W.E.
Volume Change = 0.023 ± 0.027 km3/yr
Area Altitude Distribution
Area (km2)
Muir total area = 118 km2
Area Averaged Elevation = 1120 m
Elevation (m)

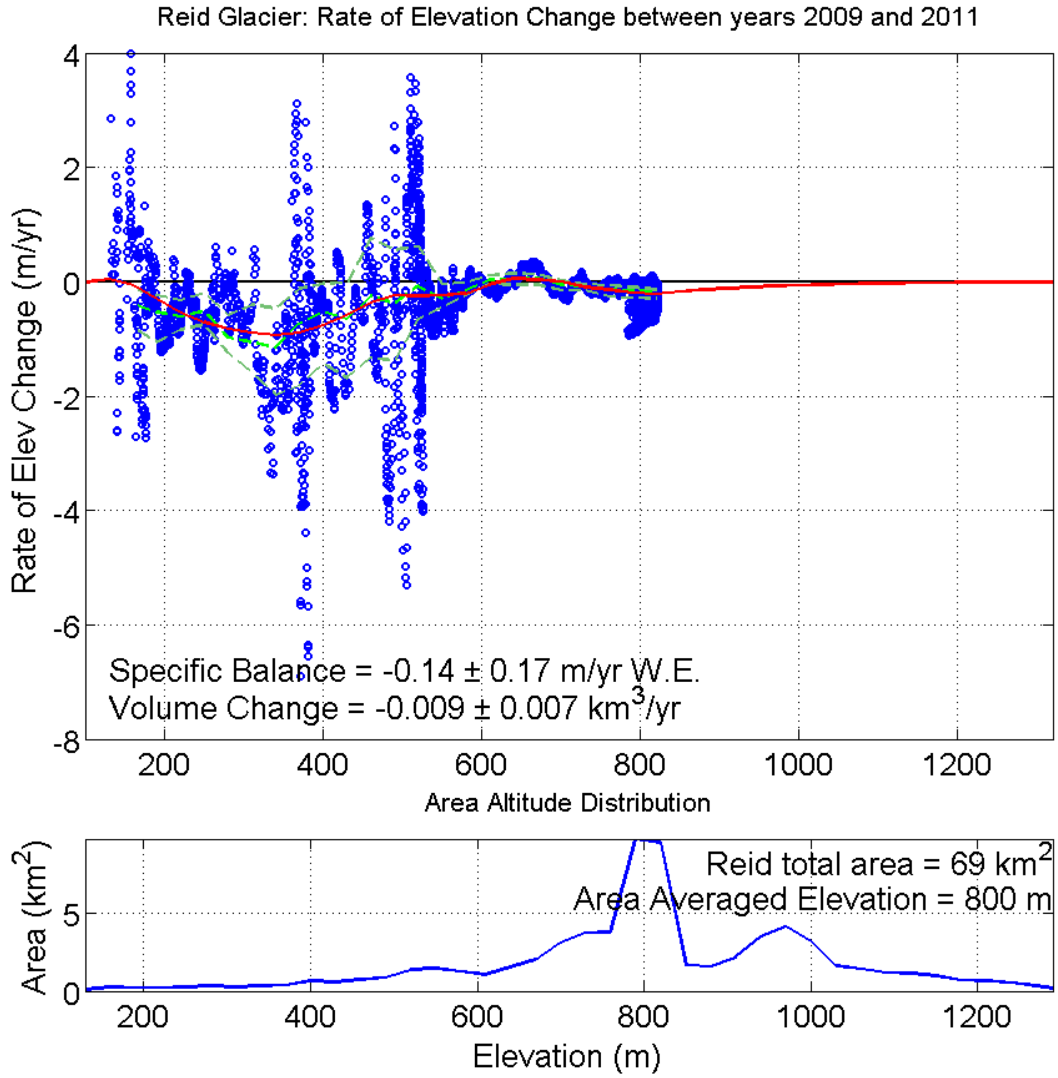


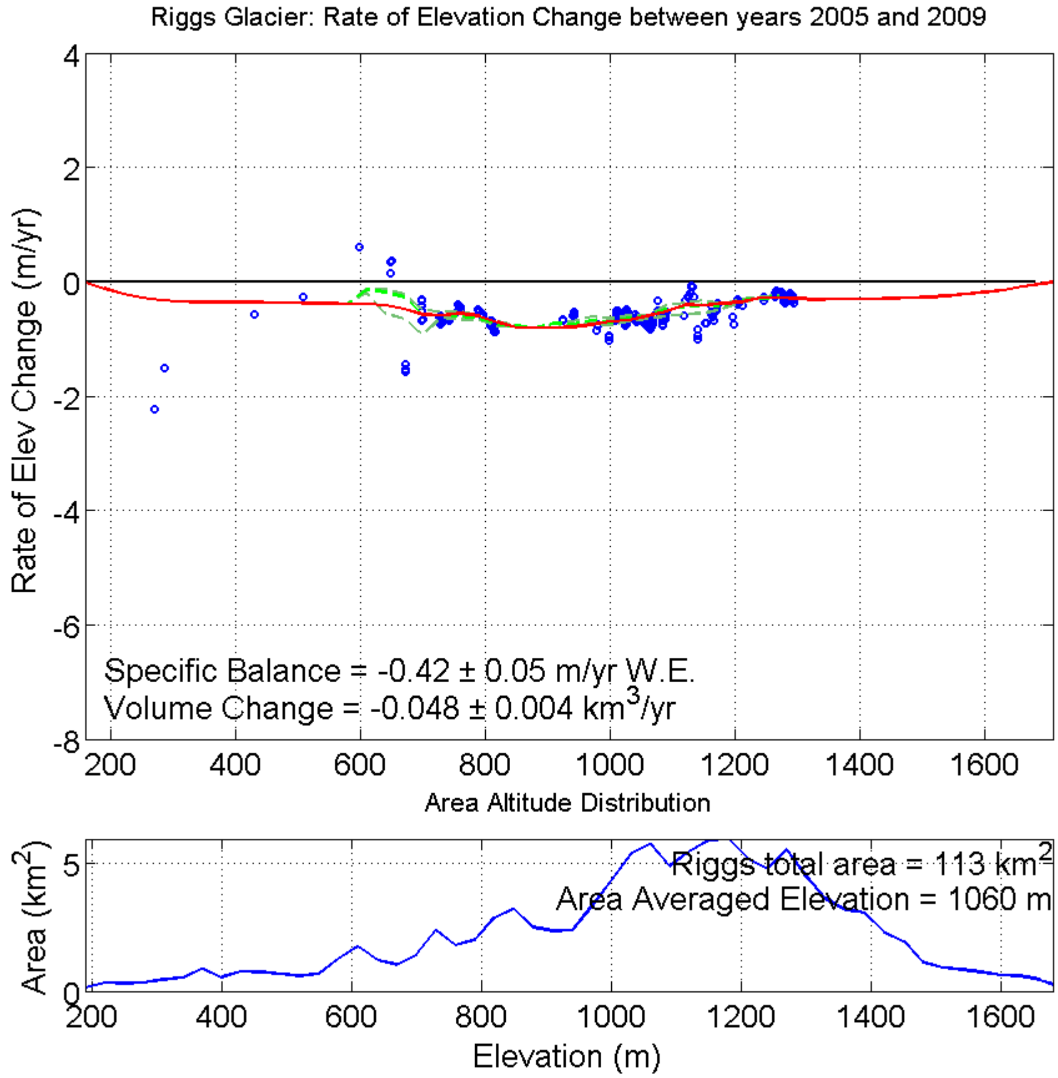
Reid Glacier: Rate of Elevation Change between years 1995 and 2000
Rate of Elev Change (m/yr)
4
2
0
-2
-4
-6
-8
Specific Balance = -0.43 ± 0.08 m/yr W.E.
Volume Change = -0.029 ± 0.003 km3/yr
200
400
600
800
1000
1200
Area Altitude Distribution
Area (km2)
5
0
Reid total area = 69 km2
Area Averaged Elevation = 800 m
200
400
600
800
1000
1200
Elevation (m)

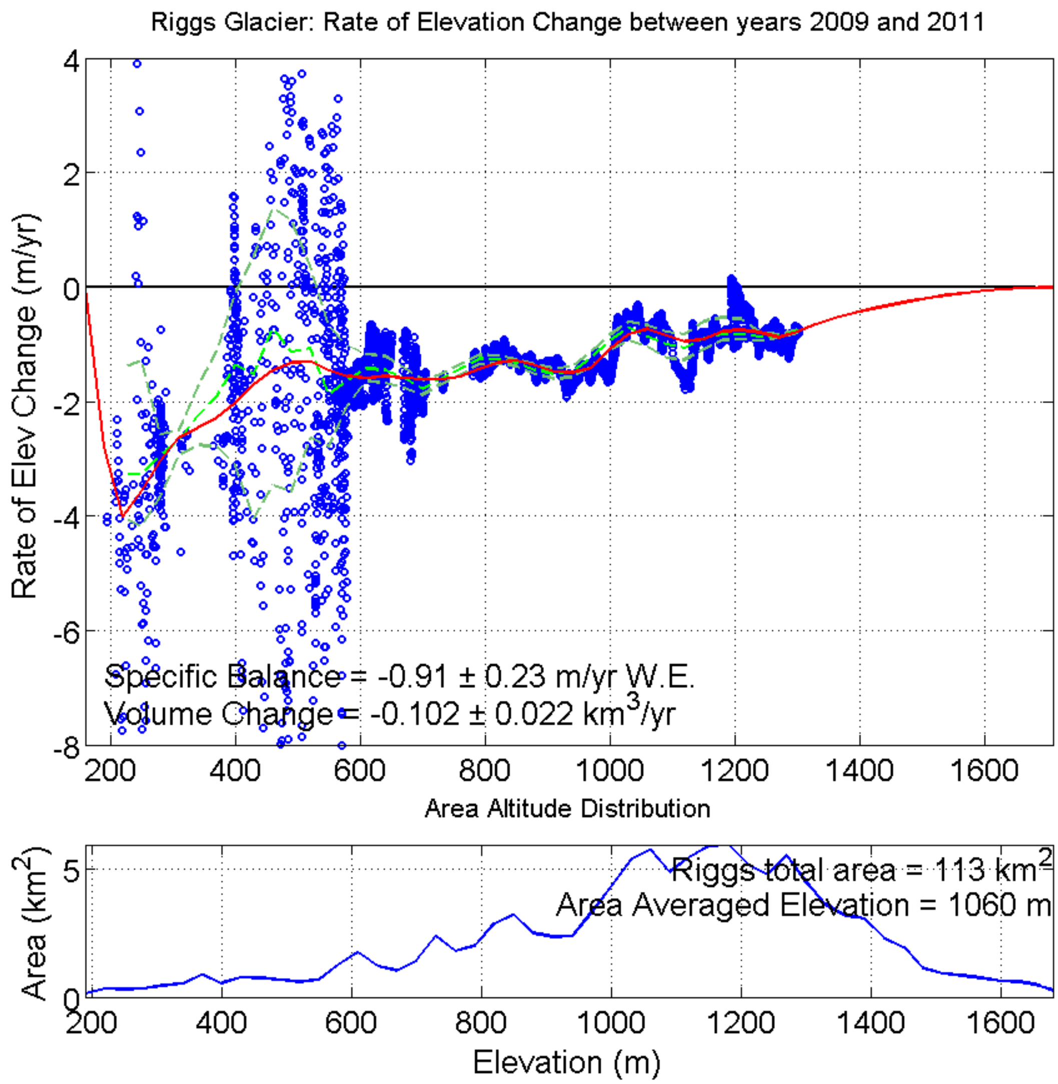


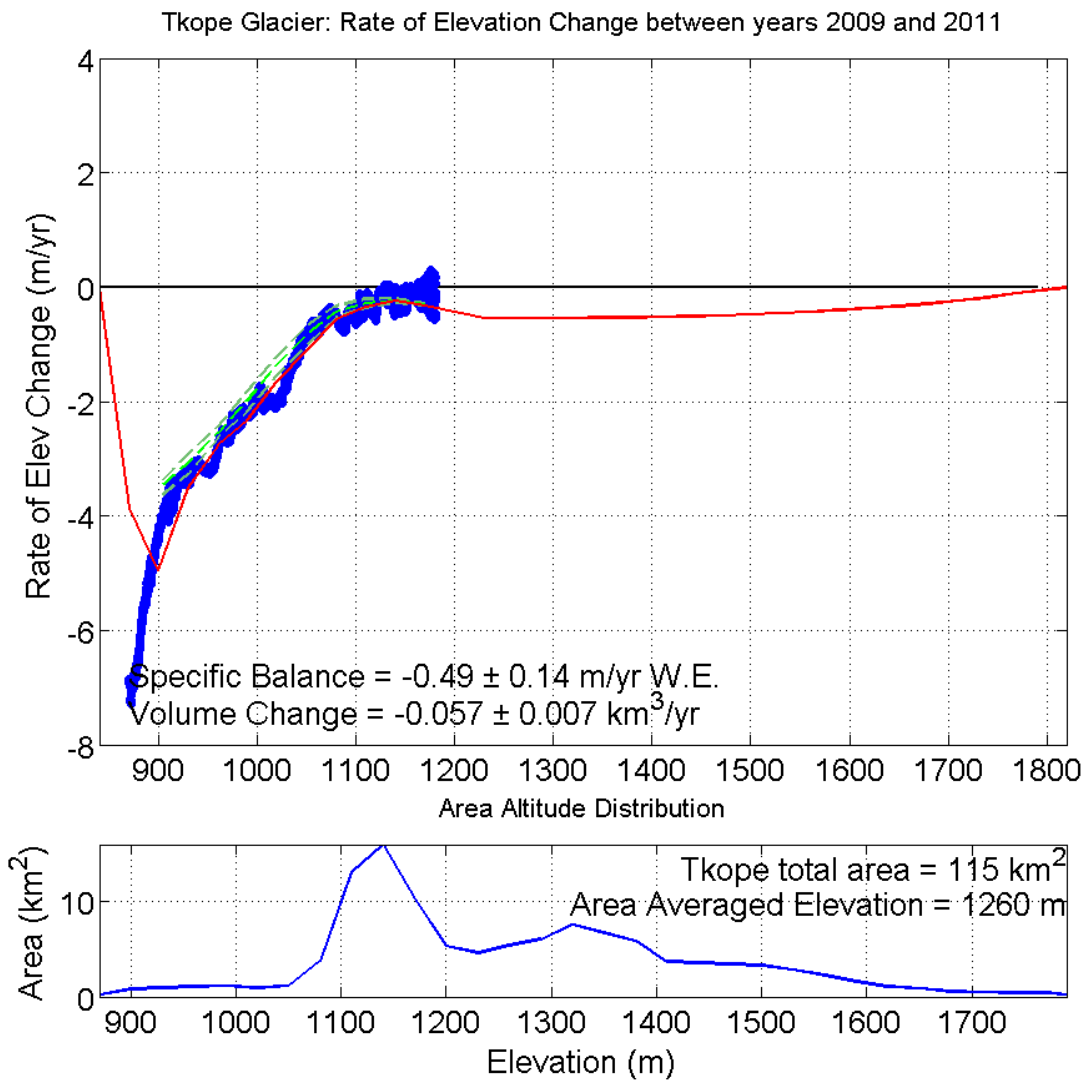
Reid Glacier: Rate of Elevation Change between years 2000 and 2005
Rate of Elev Change (m/yr)
4
2
0
-2
-4
-6
-8
200
400
600
800
1000
1200
Specific Balance = -0.89 ± 0.05 m/yr W.E.
Volume Change = -0.061 ± 0.003 km³/yr
Area Altitude Distribution
Area (km²)
5
0
Reid total area = 69 km²
Area Averaged Elevation = 800 m
Elevation (m)


Reid Glacier: Rate of Elevation Change between years 2005 and 2009
Rate of Elev Change (m/yr)
4
2
0
-2
-4
-6
-8
200
400
600
800
1000
1200
Specific Balance = -0.11 ± 0.02 m/yr W.E.
Volume Change = -0.008 ± 0.001 km3/yr
Area Altitude Distribution
Area (km2)
5
0
Reid total area = 69 km2
Area Averaged Elevation = 800 m
Elevation (m)


Reid Glacier: Rate of Elevation Change between years 2009 and 2011
Rate of Elev Change (m/yr)
4
2
0
-2
-4
-6
-8
Specific Balance = -0.14 ± 0.17 m/yr W.E.
Volume Change = -0.009 ± 0.007 km^3/yr
200
400
600
800
1000
1200
Area Altitude Distribution
Area (km^2)
5
0
Reid total area = 69 km^2
Area Averaged Elevation = 800 m
200
400
600
800
1000
1200
Elevation (m)


Riggs Glacier: Rate of Elevation Change between years 2005 and 2009
Rate of Elev Change (m/yr)
4
2
0
-2
-4
-6
-8
Specific Balance = -0.42 ± 0.05 m/yr W.E.
Volume Change = -0.048 ± 0.004 km3/yr
200
400
600
800
1000
1200
1400
1600
Area Altitude Distribution
Area (km2)
5
0
Riggs total area = 113 km2
Area Averaged Elevation = 1060 m
Elevation (m)


Riggs Glacier: Rate of Elevation Change between years 2009 and 2011
Rate of Elev Change (m/yr)
4
2
0
-2
-4
-6
-8
200
400
600
800
1000
1200
1400
1600
Specific Balance = -0.91 ± 0.23 m/yr W.E.
Volume Change = -0.102 ± 0.022 km3/yr
Area Altitude Distribution
Area (km2)
5
0
Riggs total area = 113 km2
Area Averaged Elevation = 1060 m
Elevation (m)



Tkope Glacier: Rate of Elevation Change between years 2009 and 2011
Rate of Elev Change (m/yr)
4
2
0
-2
-4
-6
-8
Specific Balance = -0.49 ± 0.14 m/yr W.E.
Volume Change = -0.057 ± 0.007 km3/yr
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
Area Altitude Distribution
Area (km2)
10
0
Tkope total area = 115 km2
Area Averaged Elevation = 1260 m
900
1000
1100
1200
1300
1400
1500
1600
1700
Elevation (m)

Appendix B: Abstract submitted to Southwest Alaska Science Symposium

Abstract submitted November 2-4 2011 in Anchorage, AK

STATUS AND TRENDS OF ALASKA NPS GLACIERS: WORKPLAN AND EARLY RESULTS

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Glaciers cover about 75,000 km^2 of Alaska's land surface and approximately one-quarter of those glaciers are located within National Park boundaries. Changes in these glaciers are of global importance, since over the past half-century Alaskan glaciers have contributed more than a quarter of the total sea level rise attributed to melting glaciers and ice caps worldwide. Local impacts of glacier retreat are important, too, and include ecological changes, hydrological threats to major infrastructure, and significant changes in recreational viewsheds. To develop a more comprehensive understanding of the glacier resource in Alaskan National Parks and to assess the extent and impacts of recent changes to that resource, NPS recently initiated a collaborative 3-year project with investigators from University of Alaska Fairbanks and Alaska Pacific University. The project consists of three major components: 1) map the areal extent of all NPS glaciers in the 1950s (from topographic maps) and the 2000s (from satellite imagery); 2) use existing repeat laser altimetry to estimate volume changes in a geographically diverse subset of the NPS glaciers; and 3) more thoroughly characterize historic changes to and landscape-scale impacts of 1-3 "focus glaciers" per glaciated park unit. Criteria for inclusion in the list of focus glaciers includes relative accessibility to visitors, an existing history of documentation including published and unpublished research, and representation of one of the many unique ways that glaciers respond to climatic change. In the Southwest Area Network, the current list of focus glaciers includes Aialik, Exit, and Skilak Glaciers (KNFJ), Turquoise, Tanaina, and Tuxedni Glaciers (LACL), Fourpeaked and Knife Creek Glaciers (KATM), and remnant ice in the Aniakchak Caldera (ANIA). In this presentation, we use early results from Southwest Area and other statewide glaciers to document our ongoing methodology and seek feedback on the projected outcomes of the project.

Appendix C: Fields in the hypsometry and geostatistics databases generated by the mapping component.

Hypsometry Fields

ID: glacier identification code
Name: common name of glacier, if known
Code: GLIMS-standard code describing glacier type
Latitude: Latitude of glacier centroid in decimal degrees
Longitude: Longitude of glacier centroid in decimal degrees
Area: glacier area (km^2)
Elev_Min: minimum (terminus) elevation (m)
Elev_Max: maximum (headwaters) elevation (m)
Median: area-weighted median elevation (m)
Mean: area-weighted mean elevation (m)
B0: glacier area in 0 to 50 m elevation bin (km^2)
B50: glacier area in 50 to 100 m elevation bin (km^2)
B100: glacier area in 100 to 150 m elevation bin (km^2)
Etc: bins continue to highest glacier elevation at 50 m increments

Geostatistics Fields

ID: glacier identification code
Name: common name of glacier, if known
Date: Year of image/data acquisition
Code: GLIMS-standard code describing glacier type
Latitude: Latitude of glacier centroid in decimal degrees
Longitude: Longitude of glacier centroid in decimal degrees
Area: glacier area (km^2)
ElevMin: minimum (terminus) elevation (m)
ElevMax: maximum (headwaters) elevation (m)
AWME: area-weighted mean elevation (m)
Kurowsky: average of highest and lowest glacier elevations (m)
Slope: mean glacier slope (degrees)
SSTD: standard deviation glacier slope (degrees)
Aspect: mean glacier aspect (degrees)
ASTD: standard deviation glacier aspect (degrees)

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National Park Service
U.S. Department of the Interior

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